A MODEL FOR CONJUNCTIVE USE OF GROUND AND SURFACE WATERS OF BARI DOAB TRACT IN PUNJAB

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By
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CERTIFICATE

This is to certify that the thesis entitled "A Model For Conjunctive Use of Ground and Surface Waters of Bari Doab Tract in Punjab" is record of work carried out under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

A linear programming model for the conjunctive utilization of ground and surface waters is presented. The model incorporates a single water use, viz., Irrigation. For a one year period of operation, the irrigated acreages under each crop grown in the area and the monthly water releases from the two sources available-canals and tube wells, to meet the water requirement of crops are determined so that the benefits from the irrigation activity is maximised. In developing the model it is assumed that the hydrologic inputs are deterministic.

The model developed, is applied to the Bari Doab Tract in Punjab State of the Indian Union. This area includes the two districts of Amritsar and Gurdaspur and lies in between Ravi and Beas rivers of the Indus river basin.

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CHAPTER - I

INTRODUCTION

Water is a renewable source that follows in nature a path called the hydrologic cycle. The details of the hydrologic cycle are described and analyzed at length in texts on hydrology(1,2,3). We will limit ourselves here to point out that oceans are the sources of all waters on the earth. Energy originating in the sun and reaching this planet causes the evaporation of water from the oceans. Meteorological processes results in the precipitation of part of the atmospheric water vapours. Water then reaches the ground as liquid (rain, dew) or is solid state (snow) and eventually finds its way back to the ocean, thus closing the hydrologic cycle.

The determination of the casual relationship between the application of water and its use, was the starting point of man's attempt to top the hydrologic cycle at one or more points to utilize water for a variety of pruposes in his social practice. Man's

attempt to take advantage of certain aspects of the hydrologic cycle, gave rise to water resources projects of a wide range of sophistication. In their simplest form, such projects are nothing more than primitive facilities for the storage of rainfall in cisterns, for human consumption and domestic use. In the deltaic region where agriculture first developed, the river flood level being higher than the surrounding country, natural flooding for irrigation could be easily done. Open cuts were made in the river banks to bring the water from lower levels and take it further away from the river. Once the necessity of control was realised, some primitive type of head regulator was evolved. When the rivers fell very low these open cuts could not draw any water, and then a sort of bund across the river made of wood and earth on stores was evolved from which sprang up the masonary weirs and dams.

Modest advances in utilization of waters can be detected in the fourteenth century during the Rennaisance period. For the scientific study of water resources, we owe to Daniel Bernoulli, who in 1738 applied

the concept of conservation of matter to hydrodynamics. At about the same time, d' Alembert showed that Newton's third law of motion applies equally well to moving bodies (hence, to flowing water) as to bodies at rest. Toward the end of eighteenth century, Chezy derived the formula describing the flow of water in open channels. An important land mark in the development of modern thought in relation to water problems is the treatise published by Darcy in 1856 regarding flow of water in porous medium. A concise summary of the historical development of scientific thinking related to water resources can be found in Chow's, Hand-book of Applied Hydrology (4).

A common characteristic of most regions is a space and time in balance of water demand and natural supplies. Man in his social practice finds that periods of highest rainfall do not coincide with periods of maximum water demand. Table I illustrates the relative disparity between monthly water supply and irrigation demand in the Bari Doab Tract, Punjab.

TABLE I

Monthly fluctuations in rainfall and water demand in UBD tract, Punjab as percentage of yearly total (5).

Month	Rainfall	Water demand for agriculture
Jan.	5.6	3.2
Feb.	6.1	3.9
March	5.0	7.5
April	2.8	10.0
May	1.6	13.1
June	6.9	13.4
July	28.0	11.5
August	29.6	10.8
Sept.	9.6	11.0
Oct.	1.3	7.5
Nov.	0.4	4.1
Dec.	3.1	3.8
Total	100.0	100.0

To remove this time imbalance, man in his social practice has resorted to impounding excess water supplied during times of high runoff and releasing the stored water during times of demand. Historically, water projects were first conceived of as single purpose project. We have in the course of recent history seen the evolution from this concept to multi-purpose construction. The use of multiple purpose reservoirs in regional development schemes is today a well established practice (6).

During the last ten years, the development of water resources in any basin is being thought of as an integrated development (conjunctive use) of ground and surface waters. Consequently conjunctive use of ground water should be considered wherever major aquifers of good water yielding properties exist in a region in which large volumes of surplus water can be stored and withdrawn cyclicly. A distinctive advantage of storing water underground over a surface reservoir is the water stored is not subject to evaporation losses. Furthermore savings may be achieved by leaving the canals

unlined, because seepage from canals percolates to the aquifer and is not lost. Such a dual system while certainly advantageous from the view of water conservation may require increased capital outlay for wells, reservoirs, pipe lines, canals, pumping station and artificial drainage facilities. A comprehensive survey of the pros and cons of conjuctive water use is given by Todd (3).

A system under conjunctive water use may offer the alternatives of extracting water from a number of aquifers, by pumping, or from reservoirs by gravity flow and/or replenishing the aquifer with recharge facilities. Given all these sources and facilities the major question we will be faced with is to what extent each of them must be used on to what scale expanded to give the most desirable results. Modern operational techniques like linear programming and dynamic programming offer possibilities for finding solutions to problems of optimum timing, scale of development and use of alternative water sources.

The present study will use the problems of agricultural development in Punjab as its source of inspiration for the development of a deterministic Linear Programming Model for a water resources system comprising of canals, tube wells and drainage and where irrigation is the only water activity. Water requirements of the crops that are grown is met by a conjunctive use of ground and surface waters through tube-wells and canals respectively. The model as developed will include as input data, the hydrologic and economic characteristics of the water basin. Our objective will be to determine the extent of allocation of irrigated area to alternative crops and the seasonal water releases from the two sources, canals and tube-wells, to meet the seasonal water requirements of the crops, for a one year period of operation. The policy we will be determining will be such that the returns function for the irrigation activity, subject to a set of constraints is maximised. Chapter III of this study deals with all these.

In Chapter IV we will apply the model developed, to the Bari Doab Tract Comprising of Gurdaspur and

Amritsar districts of the Punjab State. The Bari Doab Tract is situated between the two rivers Ravi and Beas of the Indus River system. The available hydrologic and economic data for this region is sufficient for the limited scope within which a conceptual model is developed in Chapter III.

The results and conclusion of this study are presented in Chapter V. Appendix A gives the References and Appendix B the computer program used to solve the optimization problem posed.

CHAPTER - II

REVIEW OF LITERATURE

One of the first to state specifically the needs for conjunctive ground and surface waters use and suggest steps to be followed was H. Conklin (7) in 1948. He proposed the following conditions necessary to the implementation of conjunctive water use.

1) Ground water of the alluvium is readily accessible to extraction by pumps;

2) The alluvium is sufficiently permeable to yield water in commercial quantities;

3) The alluvium is recharged naturally with water or is susceptible of being recharge artificially to such an extent that heavy commercial drafts can be sustained; and

4) If artificial recharging is necessary it can be done at feasible cost.

Conklin's work to help establish the fact not generally appreciated then, that "ground water is merely water beneath the earth's surface and that surface water is merely water on the earth's surface. The same drop of water moves from above the surface to below the surface and vice-versa. Whether above or below, it follows the same physical laws at all time", opened the doors for an integrated development of ground and surface waters.

The efficient management of water resources continued to attract great attention in the face of increasing demands of water for variety of purposes coupled with the limited availability of natural water resource. An increasing necessity to consider water problems not at a local level but at a regional level and also an integrated approach for the utilization of the available water resources was felt. The problems as formulated continued to become more and more complex and available conventional methods proved incapable for their solution. Dantzig's development of Linear Programming technique in 1947 a and Bellman's (9) development of technique of

dynamic programming provided the mathematical tools necessary for the solution of vexing water problems. The use of system techniques and the advent of computer technology provided the impetus for a considerable extent of work towatds efficient water management.

Hall and Buras (10) have outlined the potentials of dynamic programming to multistage decision problems regarding allocation of water to various alternative uses, choice among alternative reservoir sites and optimum scale of development of a water conservation system.

What started as optimisation of a few particular physical parameters, soon developed where economics played a major factor in the development of water projects involving optimum water resource allocations. Maass et al give a comprehensive information of budgeting and investment policy and the relationship between income distribution and the economics of water resource projects.

Buras in 1963 (11)used dynamic programming in the operation of a three state system including

one surface reservoirs, one aquifer, one recharge facility and two agricultural fields toward which irrigation water would be diverted from the surface reservoir or the aquifer.

Fowler in 1964 (12) approached conjunctive use problem from the engineering point of view. He suggested the following steps toward the development of a operational plan for optimum conjunctive use of ground and surface water.

1) A thorough geologic investigation has to be made and with the estimates of the geometry of the geologic formation and hydraulic aquifer properties an analog of the hydrologic basin can be constructed.

2) The hydrologic history of the river basin has to be studied to understand the factors relating to the hydrologic inputs and outputs.

3) With the construction of an operational analog model of the system, an optimal operational policy can be developed.

4) To implement the optimum policy developed and to overcome legal and financial bottle

necks, an operating agency with adequate powers to control or cooperate in the control of the various available water resources has to be established.

Chun et al in 1964 (13) describe the development of an analog model of the water supply, distribution and replenishment system of the Los Angeles basin. The basis was divided in to 81 polygons of varying sizes and the parameters of the hydrologic equation were fed into a computer for each of the polygons. Using historical data collected over several years, the simulated behaviour of the analog was tested against the historic behaviour of the physical system. This work is probably the most comprehensive and detailed regional water plan.

While considerable work was being done in the conjunctive utilisation of ground and surface waters, legal aspects assumed importance. Valentine in 1964 (14) gives a lucid commentary on the legal aspects, constraints and approaches to be considered in the planning of conjunctive water use. According to Valentire the uncertainties in the knowledge of hydrologic processes is the major reason for the lack of a comprehensive

ground water law behind the established surface water legislation.

The Los Angeles basin study (15) includes an outstanding economic analysis. However due to the relative unimportance of agriculture in the Lavy Vegas Valley, the study did not include the consideration of the complex problems of agricultural flexibilities.

Considerable work has been done in the area of conjunctive use and for situations analogous to the scope of the present study, by the Center of Population Studies, Harvard University. Douglas V Smith in 1970 (16) gives a lucid and comprehensive report on Irrigation Planning Models and the present study owes considerably to this work.

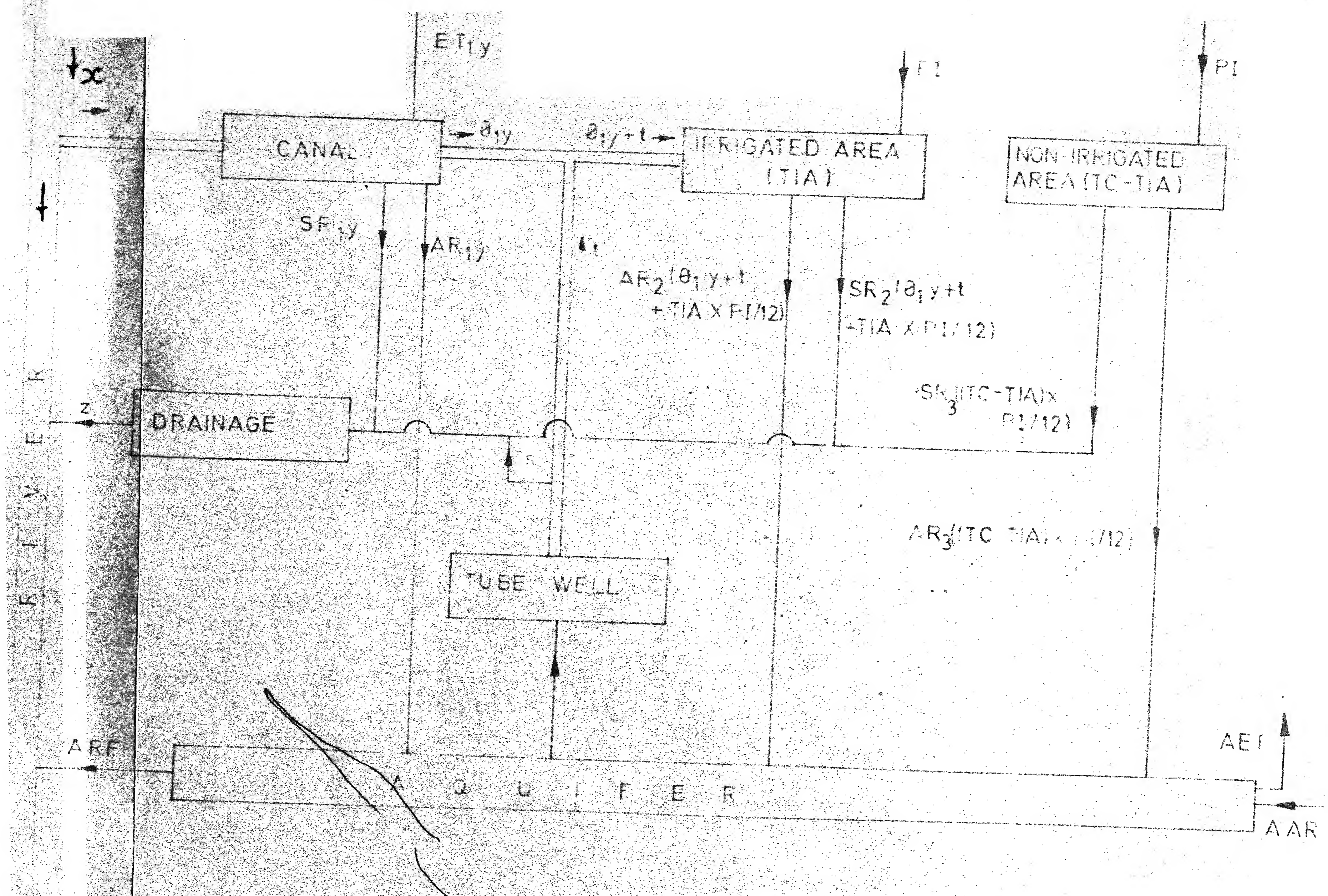


Fig. 3.1 Schematic representation of the model

CHAPTER III

CONCEPTUAL MODEL

3.1 INTRODUCTION

In this chapter we will develop a conceptual model for the conjunctive use of ground and surface waters for a single purpose viz., irrigation. We will consider a one year period of operation consisting of monthly seasonal intervals. Our objective will be to determine the extent of acreages for the various crops and the seasonal water releases from the two sources, canals and tube wells to meet the seasonal water requirements of the crops. The policy we will be determining will be such that the returns from irrigation subject to a set of constraints will be maximum. In developing the model we will make an assumption that all input data are deterministic in nature. Figure 3.1 gives the achematic representation of the model we will be developing.

3.2 SYSTEM COMPONENTS

3.2.1 Cropped Area:

In the cropped area different crops having

different seasonal water requirements, different yield and different value per pound are grown. The cropped area is subdivided into two zones, irrigated and non-irrigated areas. Natural precipitation in the area is available to meet part of the seasonal water requirements of the crops. Additional water over this amount is to be met by the seasonal water releases from canals and tube wells. Of the water delivered to this area, part of it will be lost as surface run-off, aquifer recharge and non-beneficial evapotranspiration.

3.2.2 Canals:

The canal system takes off from the river at the canal headworks and delivers water to the irrigated area. In the period of transit from canal head works to the irrigated area, part of the water that is diverted to the canals will be lost as surface runoff, aquifer recharge and non-beneficial evapotranspiration. Engineering and economic factors will impose a maximum value for the canal capacity. The canal system is not bound to be operated during the entire season. Due to routine and also unexpected necessities

of repairs etc., the efficiency of the canal system will be less than unity. During a season the demand from canals will have a peak period and hence the ratio of peak to average demand is also to be considered. The operations cost for canals is given in rupees per acre feet of water diverted to the canal system.

3.2.3 Tube-wells:

The tube well system pumps water from the aquifer and delivers it to the irrigated area. We will also consider the possibility of the tube well system pumping water direct to the drainage system. Similar as in the case of the canals, the tube well system too will have a maximum capacity imposed by engineering and economic factors, will not operate during the entire season, will have an efficiency less than unity and the ratio of peak to average demand will also have to considered. Although strictly the operations cost for pumpage will be related to both quantity and extent of lift, in our model we will assume this cost as given only in rupees per acre-feet of water pumped.

3.2.4 Drainage:

The drainage system collects the surface runoff from the canal zone, irrigated and non-irrigated areas and the direct pumpages into it if any from the tube wells system and delivers it to the river. Similar as in the case of canals and tube wells, the drainage system too will have a maximum capacity imposed by engineering and economic factors, will not operate during the entire season, will have an efficiency less than unity and the ratio of peak to average demand will also have to be considered. While delivering the water to the river; as pumpage will be necessary, the operations cost for the drainage system will be strictly related to both quantity and extent of lift. However in our model we will assume that this cost is given only in rupees per acre-feet of water delivered.

3.2.5 Aquifer:

It is feasible to exploit the underlying aquifer system for irrigation use by pumpage of water from it through a tube well system. Geologic, hydrologic

and economic factors will impose a maximum value for the annual pumpage from the aquifer system. Natural aquifer recharge from adjoining aquifers, aquifer recharge from canal zone, irrigated and non-irrigated areas form the input into the aquifer system. Besides the water that is pumped out by the tube well system, water will be also leaving the aquifer in the form of evaporation and aquifer return flow to the river.

3.3 SYSTEM PARAMETERS:

Having explained the system components in the preceding section, we will now proceed in this section to define the system parameters.

3.3.1 Cropped Area:

3.3.1.1. Input Variables:

(i) TC = total cropped area in acres

(ii) TIA = total area available for irrigation in acres

(iii) λ_j = fraction of the irrigated area allotted for the jth crop. j= 1, . . .J where J is the total number of crops grown.

(iv) WR_{ij} = water requirement of the jth crop during the ith season, in inches, i=1, . . . I, where I is the total number of seasons and j = 1, . . . J.

(v) YPA_j = yield per acre of the jth crop, in pounds per acre, j = 1, . . . J

(vi) VPP_j = value per pound of the jth crop, in rupees per pound, j = 1, . . . J

(vii) PI_i = natural precipitation in the area during the ith season, in inches.

(viii) SR_2, AR_2, ET_2 = fractions of water delivered to the irrigated area that is lost as surface runoff, aquifer recharge and non beneficial evapotranspiration respectively.

(ix) SR_3, AR_3, ET_3 = fraction of water delivered to the non-irrigated area that is lost as surface runoff, aquifer recharge and non-beneficial evapotranspiration respectively.

(x) θ_2 = fraction of water delivered to the irrigated area that is used to meet the water requirements of crops. $\theta_2 = 1 - SR_2 - AR_2 - ET_2$.

3.3.1.2 Operating Variables to be Determined:

(i) A_j = irrigated area of the jth crop

$j = 1, \ldots J$

3.3.2 Canals:

3.3.2.1 Input Variables:

(i) x_i = discharge in the river at the canal head-works during the ith season in acre-feet, $i = 1, --- I$.

(ii) Y = maximum capacity of canal system, in cusecs.

(iii) $d^{(y)}$ = number of days the canal is operated in a season.

(iv) $\eta^{(y)}$ = efficiency of the canal system

(v) $\gamma^{(y)}$ = ratio of peak to average demand of the canal system.

(vi) $c^{(y)}$ = operations cost for the canal system in rupees per acre-feet.

(vii) SR_1, AR_1, ET_1 = fractions of water diverted to the canals that is lost as surface runoff, aquifer recharge and non-beneficial evapotranspiration respectively.

(viii) θ_1 = fraction of water diverted to canals that is delivered to the irrigated area $\theta_1 = 1 - SR_1 - AR_1 - ET_1$.

3.3.2.2 Operating Variables to be Determined:

(i) y_i = flow diverted to canals during the ith season, in acre-feet, $i=1, \ldots I$.

3.3.3 Tube-wells:

3.3.3.1 Input Variables:

(i) T = maximum capacity of tubewell system, in cusecs.

(ii) $d^{(t)}$ = number of days the tube-wells are operated in a season.

(iii) $\eta^{(t)}$ = efficiency of the tube well system

(iv) $\gamma^{(t)}$ = ratio of peak to average demand for tube wells

(v) $c^{(t)}$ = operations cost for tube wells in rupees per acre-feet.

3.3.3.2 Operating Variables to be Determined:

(i) t_i = pumpage through tube well system for irrigation during the ith season, in acre-feet, $i = 1, --- I$.

(ii) s_i = pumpage through tube well system direct into the drainage system during the ith season, in acre-feet, $i = 1, --- I$.

3.3.4 Drainage:

3.3.4.1 Input Variables:

(i) Z = maximum capacity of drainage system, in cusecs.

(ii) $d^{(z)}$ = number of days the drainage system is operated in a season.

(iii) $\eta^{(z)}$ = efficiency ofthe drainage system

(iv) $\gamma^{(z)}$ = ratio of peak to average demand of drainage system.

(v) $c^{(z)}$ = operations cost for the drainage system is rupees per acre-feet.

3.3.5 Aquifer:

3.3.5.1 Input Variables:

(i) AAR = annual aquifer natural recharge from adjoining aquifers, in acre-feet.

(ii) AEP = annual aquifer evaporation, in acre-feet

(iii) ARF = annual aquifer return flow to the river, in acre-feet

(iv) PMR = permissible mining rate in acre-feet per year.

3.4 MATHEMATICAL FORMULATION:

Having explained the system components and defined the system parameters in the preceeding sections, we will in this section proceed to develop the mathematical formulation in the form of a Linear Programming Model.

3.4.1 Objective Function:

The objective function includes returns from the irrigated area and the operations costs for canals, tube wells and drainage

3.4.1.1. Return From Irrigation:

Annual returns from the irrigated area is the

value of the crops grown there. This will be equal to

$$\sum_{j=1}^{J} A_j \times YPA_j \times VPE_j$$

3.4.1.2 Operations Cost For Canals:

Annual operations costs will be equal to

$$\sum_{i=1}^{I} c^{(y)}{}_{x} \cdot y_i$$

3.4.1.3 Operations Cost For Tube-wells:

Annual operations costs will be equal to

$$\sum_{i=1}^{I} c^{(t)}{}_{x} \; (t_i + s_i)$$

3.4.1.4 Operations Cost For Drainage:

Annual operations costs will be equal to

$$\sum_{i=1}^{I} c^{(z)}{}_{x} \; z_i$$

where z_i is the water delivered by the drainage system during the ith season.

$$z_i = s_i + SR_1 \times y_i + SR_2 (\theta_1 y_1 + t_i)$$
$$+ (PI_i \times SR_2/12.0) \left(\sum_{j=1}^{J} A_j \right)$$
$$+ (PI_i \times SR_3/12.0) \left(TC - \sum_{j=1}^{J} A_j \right)$$

$$z_i = y_i (SR_1 + Q_1 SR_2) + t_i SR_2 + s_i$$
$$+ (PI_i/12.0) \sum_{j=1}^{J} A_j (SR_2 - SR_3)$$
$$+ (PI_i/12.0) SR_3 \times TC$$

We see that z_i is nepresented as a function of y_i, t_i, s_i and A_j.

The objective function to be maximised now becomes

$$\sum_{j=1}^{J} A_j \times YPA_j \times VPP_j - \sum_{i=1}^{I} (c^{(y)} y_i + c^{(t)} (t_i + s_i)$$
$$+ c^{(z)} \times z_i)$$

3.4.2 Constraint Equations:

The above objective function is to be maximised subject to the following constraints.

i) The seasonal diversions to canals cannot exceed the seasonal inflow into the river at the canal head works.

$$y_i \leqslant x_i$$

ii) Water diverted to canals in any season cannot exceed the canal capacity

$$\nu \times \gamma^{(y)} \times y_i / d^{(y)} \times \eta^{(y)} \leqslant Y$$

where ν is the conversion factor from acre-feet per day to cusecs.

iii) Water pumped from tube wells in any season cannot exceed the tube well capacity

$$\nu \times \gamma^{(t)} \; (s_i + t_i) \, / \, d^{(t)} \times \eta^{(t)} \leqslant T$$

(iv) Water diverted to drainage system in any season cannot exceed the drainage capacity

$$\nu \times \gamma^{(z)} \times z_i \, / \, d^{(z)} \times \eta^{(z)} \leqslant Z$$

(v) Total area of various crops cannot exceed the total available area for irrigation.

$$\sum_{j=1}^{J} A_j \leqslant TIA$$

(vi) Total water removed from aquifer in a year cannot exceed the mining rate

$$\sum_{i=1}^{I} \Big[(s_i + t_i) - AR_1 x\ y_i - AR_2\ x\ (\theta_1\ x\ y_i + t_i)$$

$$- (PI_i/12.0)\ x\ AR_2\ x \sum_{j=1}^{J} A_j - (PI_i/12.0)\ x\ AR_3 x (TC - \sum_{j=1}^{J} A_j) -$$

$$+ AET + ARF - AAR \leqslant PMR$$

(vii) Water requirement for the crops is met in each season.

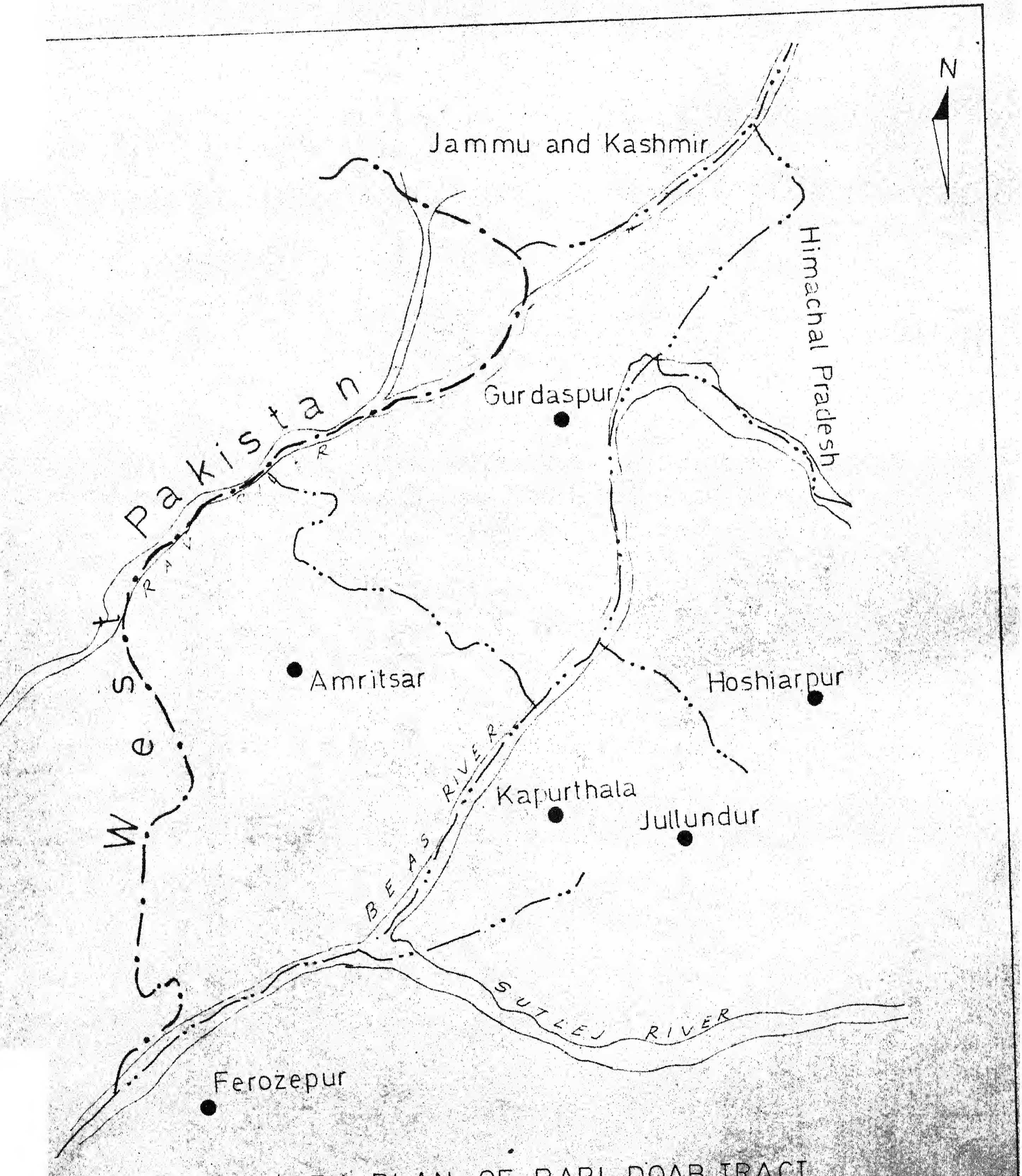
$$\sum_{j=1}^{J} A_j\ x\ WR_{ij} - \theta_2\ x\ (\theta_1\ y_i + t_i)$$

$$- \sum_{j=1}^{J} A_j\ x\ \theta_2\ x\ PI_i/12.0 \leqslant 0$$

(viii) Management considerations restricts a maximum value for the irrigated acreages under each crop.

$$\Lambda_j \leqslant \lambda_j \times TIA$$

With a conceptual model for conjunctive use of ground and surface waters for a single purpose viz., irrigation thus developed, we will proceed to apply it to a physical model in the next chapter.



FIG·4·1 INDEX PLAN OF BARI DOAB TRACT

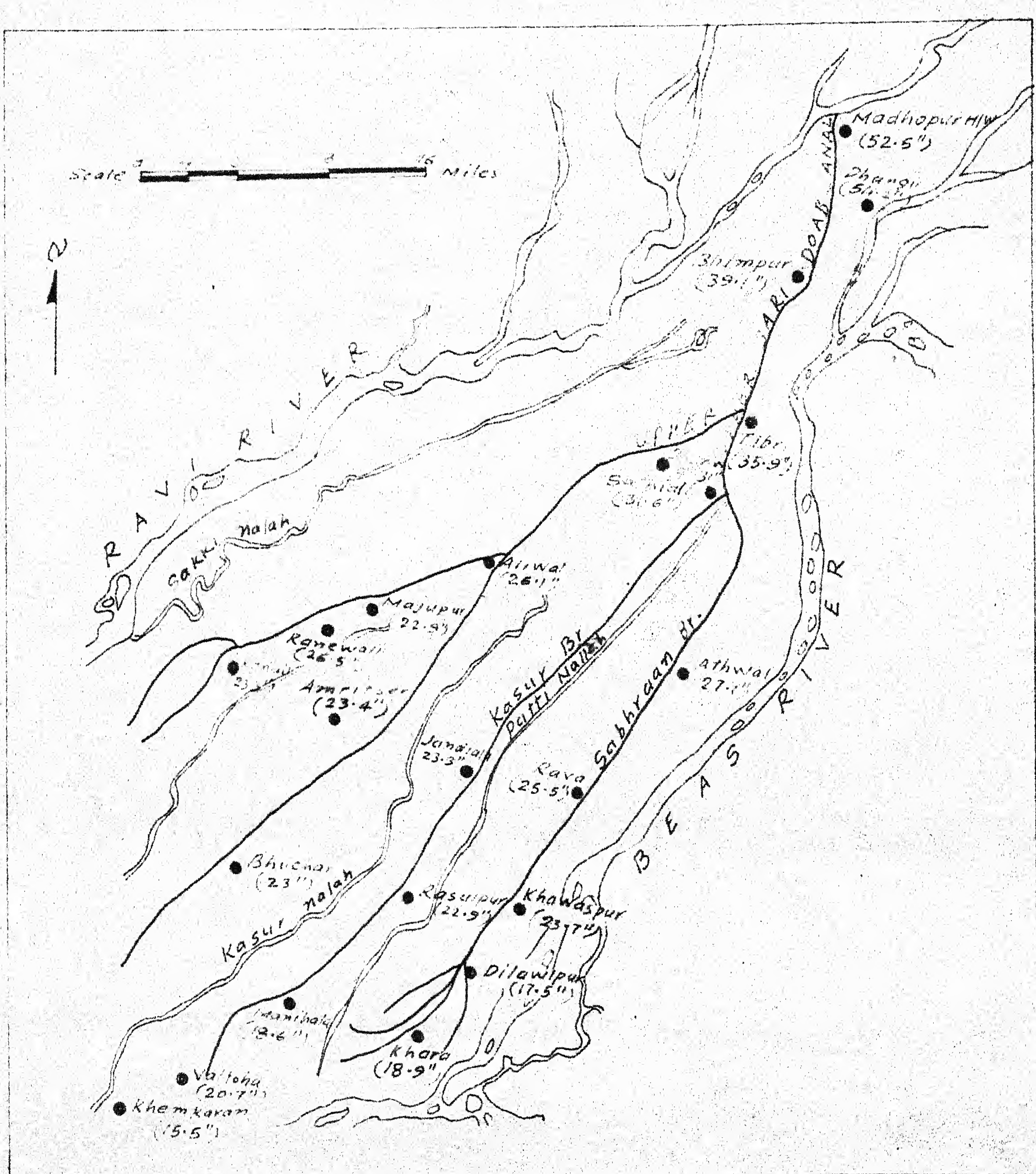
CHAPTER - IV

PHYSICAL MODEL

4.1 INTRODUCTION:

Bari Doab Tract in Punjab State of the Indian Union forms the physical model of our study. This area includes the two districts of Amritsar and Gurdaspur. The area is bounded on almost three sides by the Ravi and Beas rivers of the Indus rivers basin and by Pakistan on the fourth - western side. Figure 4.1 gives the index plan ofi the tract. Topographically Gurdaspur district lies in the narrow strip of territory stretching between the Himalayas and the Indo-Gangetic plains into which run the spurs of the Himalayas and Amritsar district lies in the Indo-Gangetic plains. The height of the Doab in the extreme North-East is 1200 feet above sea level and in the SouthWest is 685 feet and slope from North-East to South-West.

The total area of the tract is about 3,300 sq.miles. The population as per 1971 census was 30.45 lakhs. Out of this the rural population was 22.65 lakhs and urban population 7.80 lakhs signifying the dominance of the agricultural sector in this area.



BARI DOAB TRACT – AVERAGE RAINFALL AT DIFFERENT STATIONS. & UPPER BARI DOAB CANAL LAYOUT

FIG. 4·2 GENERAL DISTRIBUTION OF RAINFALL OVER BARI DOAB TRACT

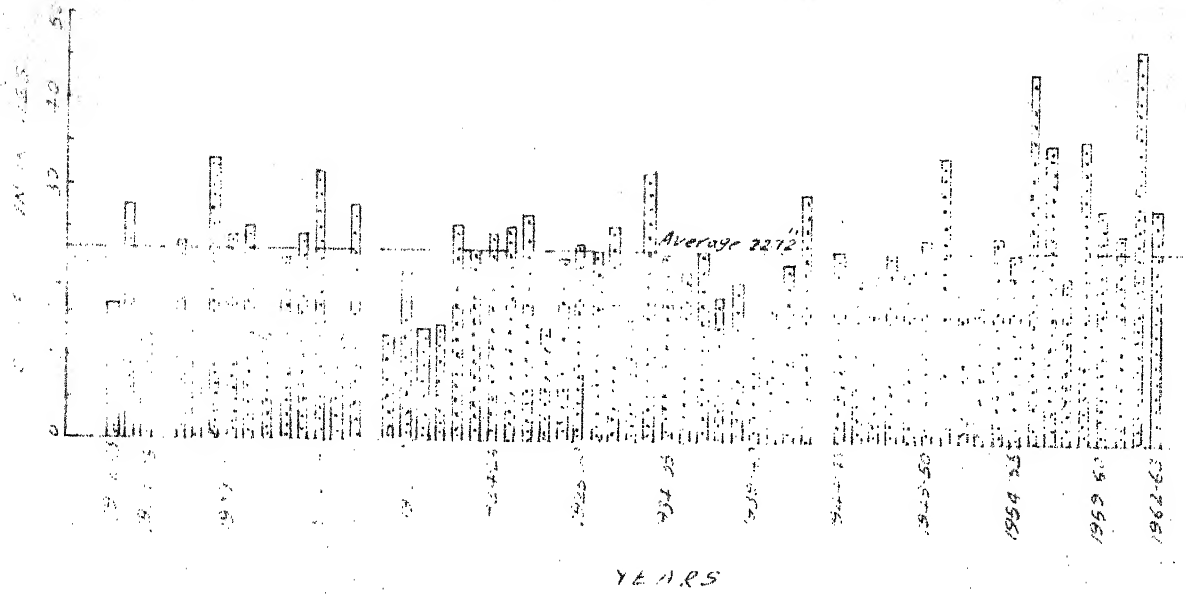


FIG. 4·3 RAINFALL IN AMRITSER DISTRICT
FROM 1902-03 TO 1962-63.

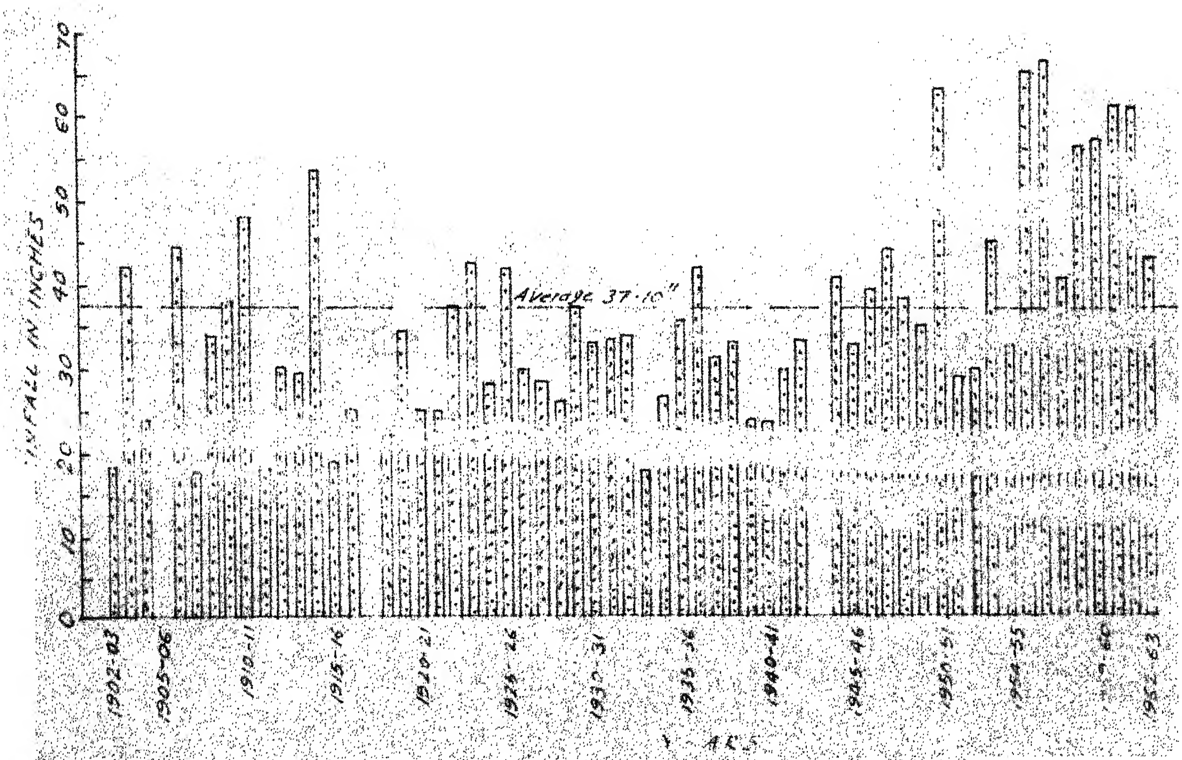
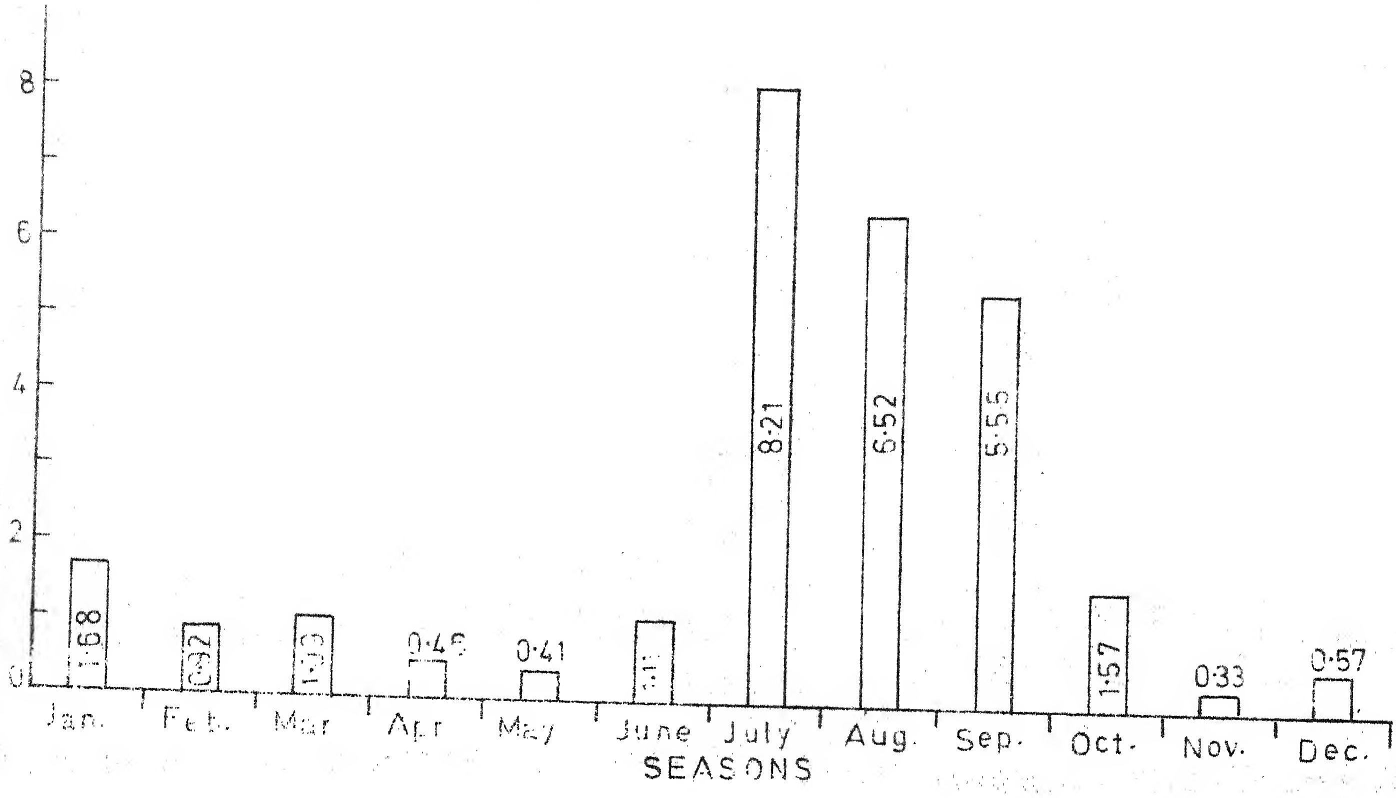
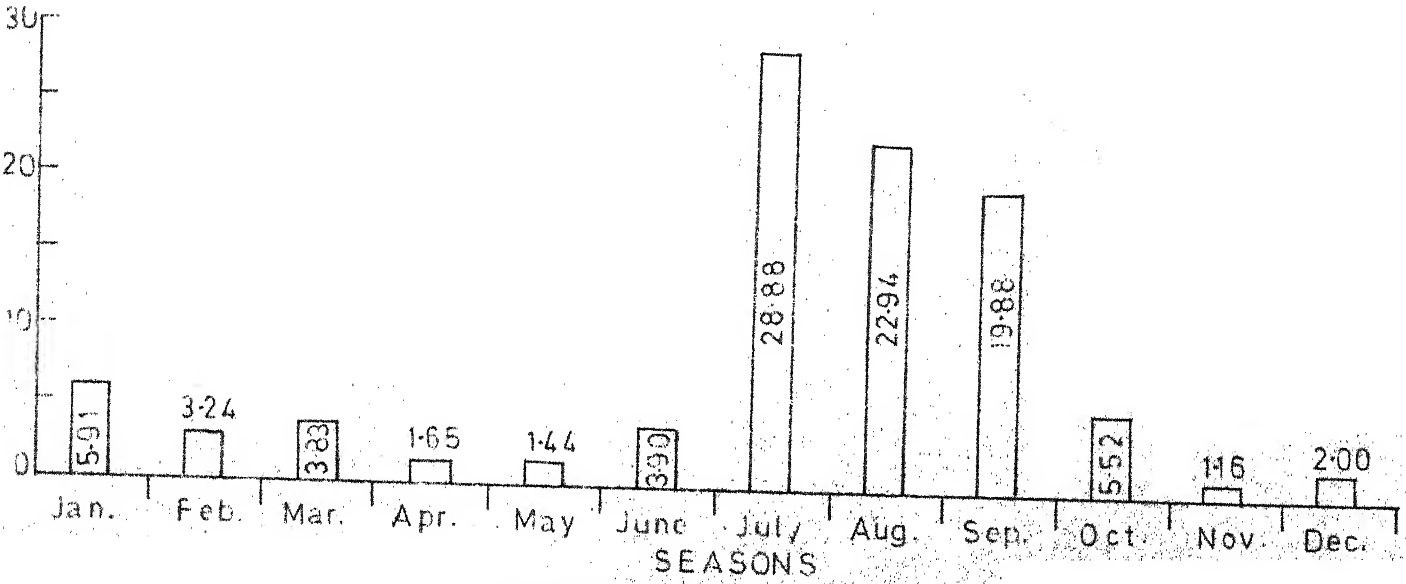


FIG. 4·3 RAINFALL IN GURDASPUR DISTRICT
FROM 1902-03 TO 1962-63



AVERAGE RAINFALL (1948-49 TO 1962-63) IN INCHES



PERCENTAGE DISTRIBUTION

FIG. 4.4 DISTRIBUTION OF TOTAL RAINFALL FOR AMRITSAR DISTRICT

4.2 METEOROLOGICAL CONDITIONS:

4.2.1 Climate:

Due to the competative proximity of the hills and the prevalence of canal irrigation, the area is temperate in the hot months from May to September. Thereafter the air becomes drier and cooler every day. Frost is common during January and February. The temperature ranges from a low of $40^{\circ}F$ in the winter months to a high of $110^{\circ}F$ in the summer months.

4.2.2 Rainfall:

The general distribution of rainfall over the area is given in Figure 4.2. We notice that rainfall decreases from North East to South West. Rainfall figures for Gurdaspur and Amritsar districts for the years 1902-03 and 1962-63 are given in Figure 4.3. The average annual rainfall for Gurdaspur district works out to 37.10 inches and that for Amritsar works out to 22.72 inches. Figure 4.4 gives the distribution and percentage of total annual rainfall over the months for Amritsar District.

4.3 GEOHYDROLOGY:

The Doab has been formed by alluvial deposits brought by the rivers Ravi and Beas. Separate Geo-hydrologic studies for Gurdaspur and Amritsar Districts have been carried out by the Geological survey of India and extensively reported by Punjab Government publications (18) and by Uppal et., al (17). These studies reveal that the substrata mostly contains medium sand. There is generally 15 to 20 feet deep soil crust at the top and is followed by water bearing strata consisting of medium or coarse sand mixed with very fine traces of clay.

Groundwater in the area occurs under confined as well as unconfined conditions. Water table is at the lowest level in June before the monsoon season and is at the highest level in October after the monsoon season. The principal sources of ground water are infiltration from rainfall, seepage from irrigation channels and irrigated fields and the subsoil flow from upper parts. Ground water in the area is generally fresh and studies (18) indicate that large scale development of ground water through tubewells is feasible

in a great part of the area. Table 3.1 gives the storage capacity of the area. Table 3.1 gives the storage capacity of the ground water reservoir as reported by Uppal et., al.

TABLE 3.1

STORAGE CAPACITY OF GROUND WATER RESERVOIR IN THE BARI DOAB TRACT

Depth Zone (in feet)	Thickness of strata (in feet)	Average Specific Yield (%)	Volume of water (Million acre feet)
15 - 50	35	12.9	9.5
50 - 100	50	17.5	18.4
100 - 350	250	17,5	91.9

In the conceptual model we had developed in the III Chapter, the aquifer system requires as input data the following: annual evaporation, annual sub-surface return flow to the river, annual aquifer recharge from adjoining rivers and a maximum permissible mining rate. All these parameters appear in the mathematical model, in the constraint equation specifying restriction on the yearly mining rate (refer 3.4.2). The same constraint when expressed in the standard manner has the right hand side constant as:

$$PMR - ARF - AET + AAR$$
$$+ (PI_i/12.0) \times AR_3 \times (TC - \sum_{j=1}^{J} A_j)$$

While applying the mathematical model to the physical model we will assume that, "PMR - ARF - AET + AAR" = 5.4 million acre-feet. This is a reasonable estimate considering the ground water capacities for different depths given is Table 3.1. A comprehensive water balance of the area would lead to a refinement for this value in future studies.

AGRICULTURE:

Wheat, maize, rice, sugar-cane and cotton are the

main crops grown in this area. The present level of cropped area for each of the crops is given in Table 4.2. Besides these main crops, we have included all other crops in one single head. Table 4.2 also gives the percentage of the total cropped area for each of these crops. While developing the constraints on the maximum permissible irrigated area for each of the crops, we will make an assumption that the percentage of the total area available for irrigation for each crop would be the same percentage value given in Table 4.2.

TABLE 4.2

CROP	CROPPED AREA OF EACH CROP (in million acres)	FRACTION OF TOTAL CROPPED AREA
Wheat	0.96	0.40
Rice	0.38	0.16
Maize	0.24	0.10
Sugar-cane	0.14	0.06
Cotton	0.08	0.03
Other Crops	0.60	0.25
Total	2.40	1.0

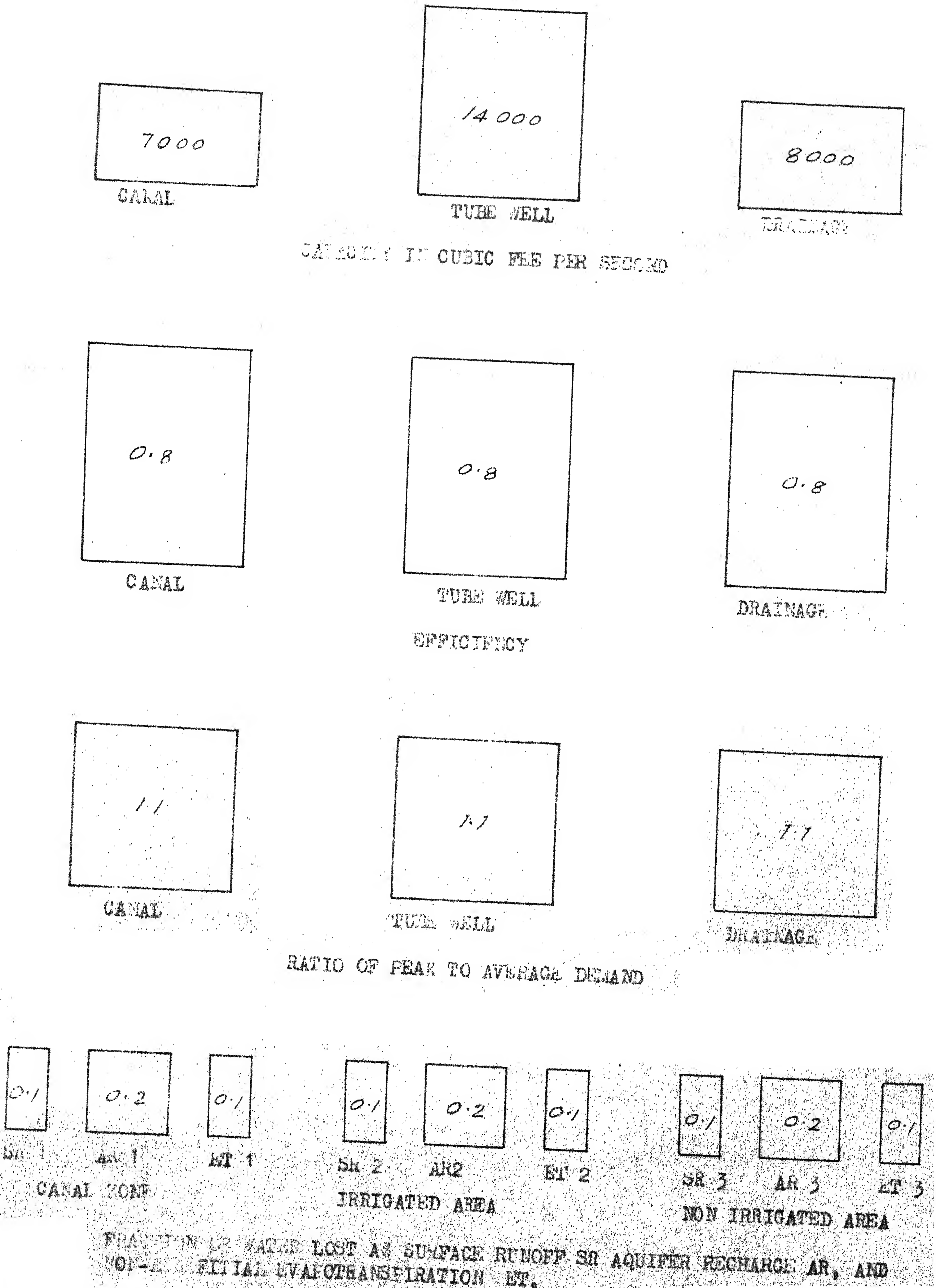


FIG. 4.5 INPUT DATA FOR THE OPTIMIZATION PROBLEM

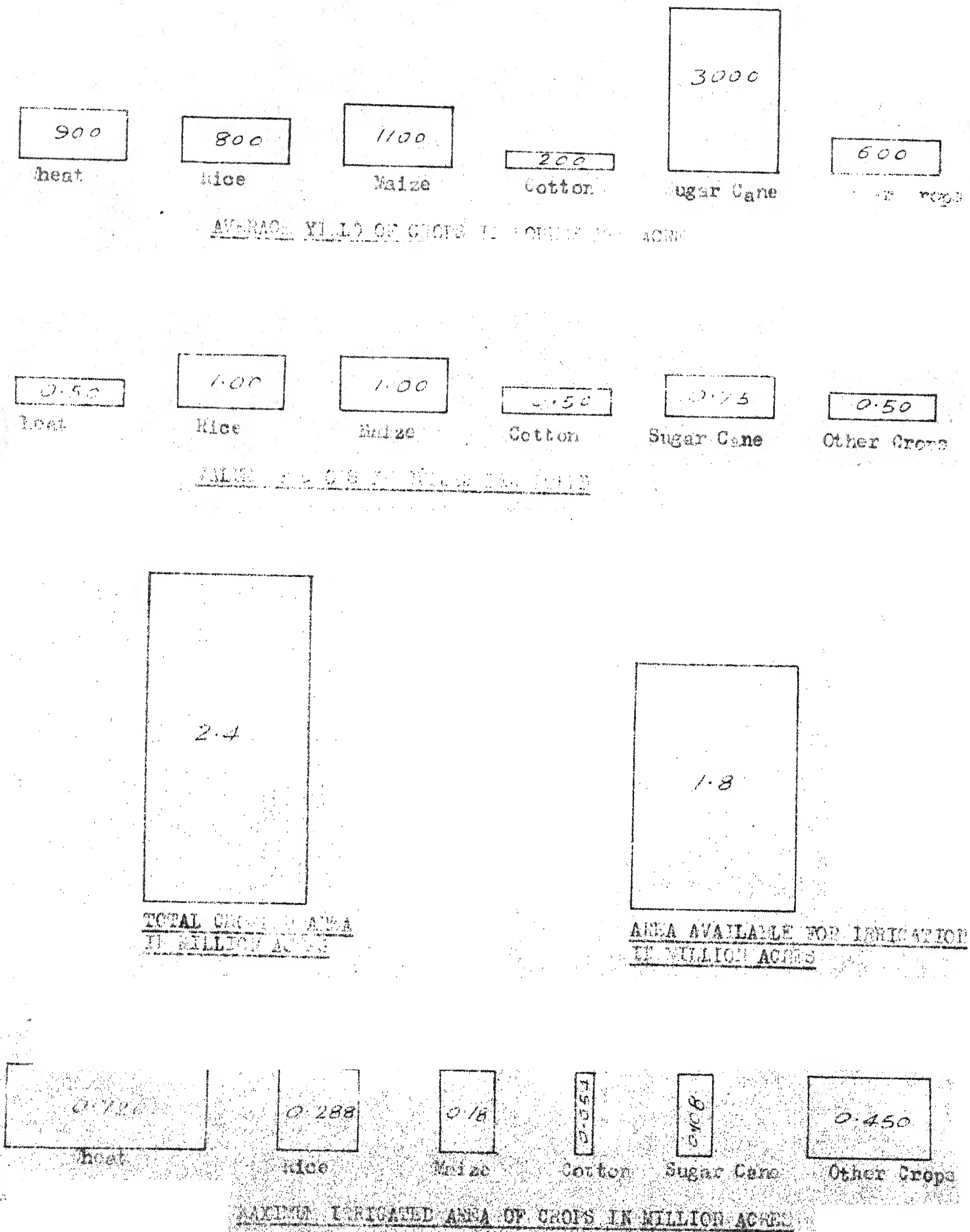
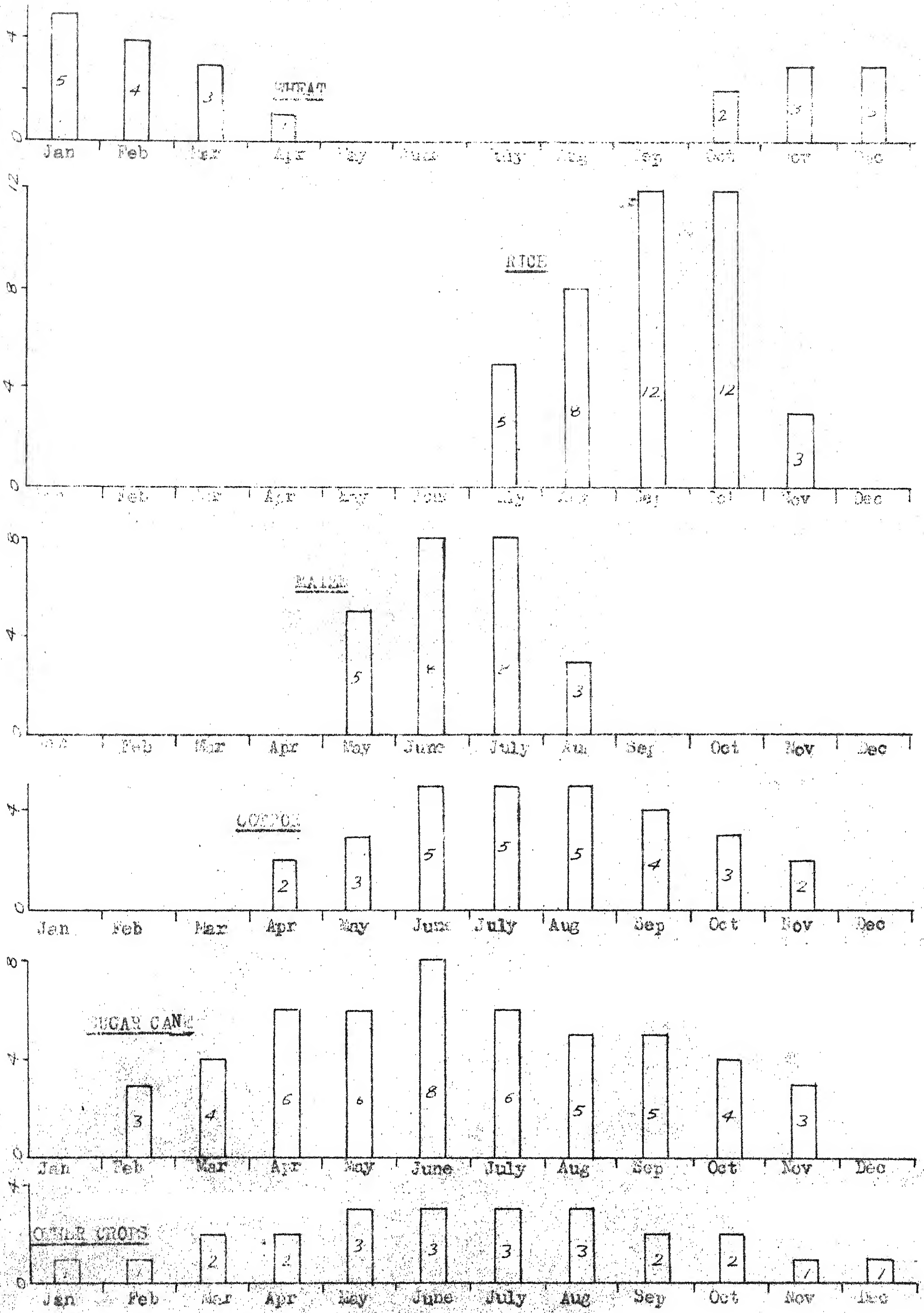
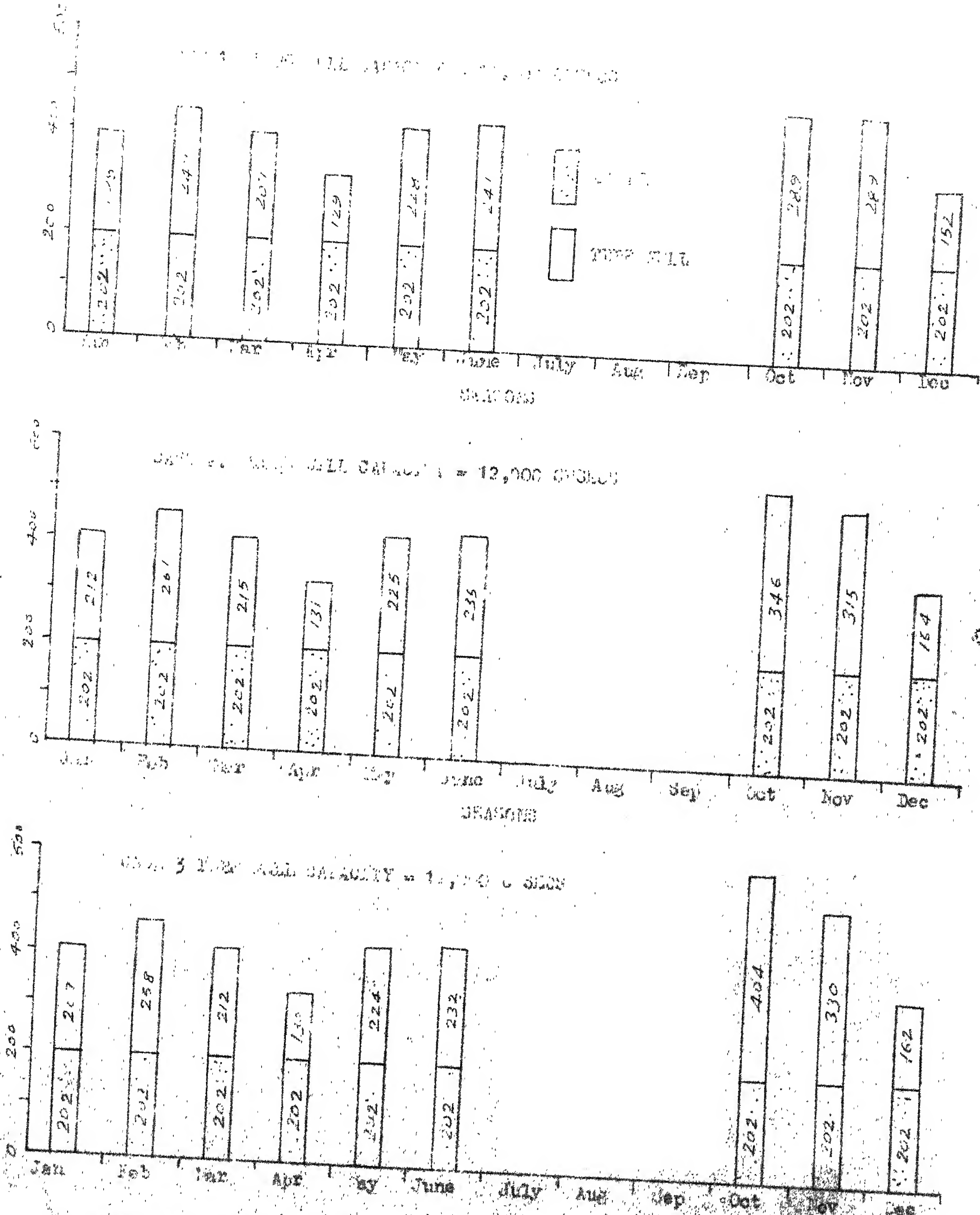


FIG. 4.5 INPUT DATA FOR THE OPTIMIZATION PROBLEM



SEASONAL WATER REQUIREMENTS FOR CROPS IN INCHES

FIG. 4.5 INPUT DATA FOR THE OPTIMIZATION PROBLEM



SEASONAL WATER RELEASES FROM CANALS AND TUBE WELLS IN THOUSAND ACRE-FEET AS PER OPTIMAL PLAN

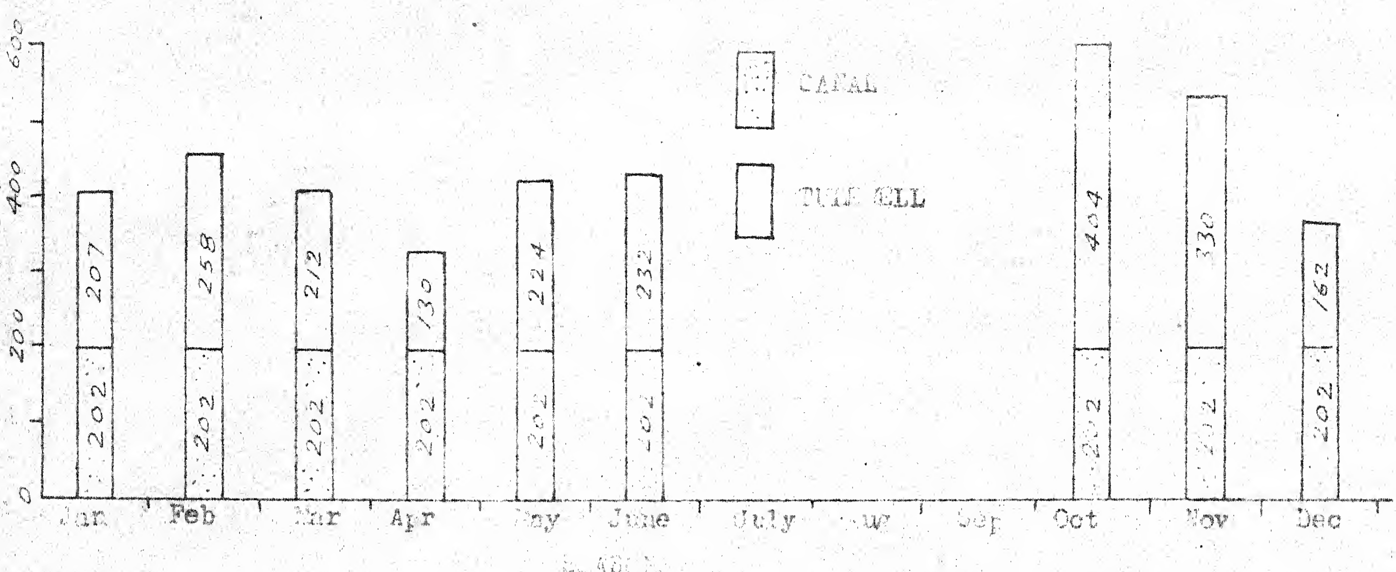
FIG. 5.3 SENSITIVITY ANALYSIS ON TUBE WELL CAPACITY

CHAPTER V

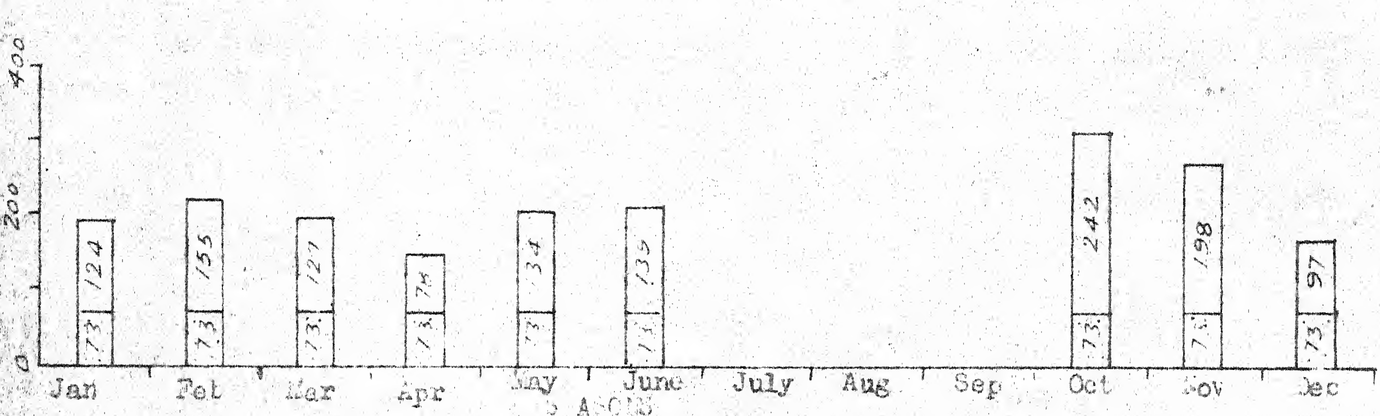
RESULTS AND CONCLUSION

5.1 GENERAL:

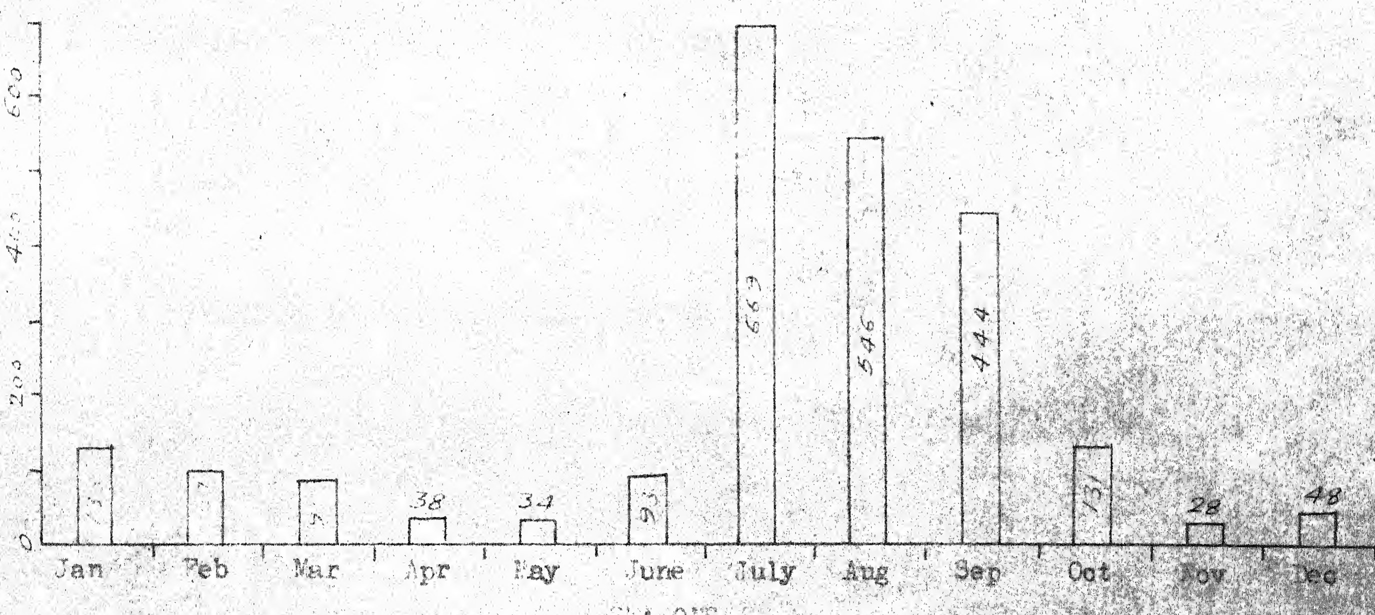
The objective function of the Linear Programming Model we formulated had 42 operating variables to be determined; the extent of irrigated areas for the 6 Crops we considered, the monthly releases from tubewells and canals for irrigation, in a year of operation and the monthly releases from tube-wells direct into the drainage system. The number of constraint equations for the Linear Programming Model we formulated was 68; 12 constraints composed by restricted river discharges, 12 constraints imposed by restricted canal capacity, 12 constraints imposed by restricted tube-well capacity, 12 constraints imposed by restricted drainage capacity, 12 constraints imposed by the necessity to meet the water requirements of the crops, in all the above cases one each for the 12 months in a year's operation, 1 constraint imposed by restricted mining rate from the aquifer, 6 constraints imposed by restricted area available for irrigation for the individual crops considered, and 1 constraint imposed by restricted area available for irrigation.



SEASONAL WATER RELEASES FROM CANAL AND TUBEWELLS IN THOUSAND ACRE-FEET AS PER THE OPTIMAL PLAN



NET WATER AFTER LOSSES IN THOUSAND ACRE-FEET FROM CANALS AND TUBEWELLS TO MEET THE WATER REQUIREMENT OF CROPS



NET WATER AFTER LOSSES AVAILABLE FROM NATURAL PRECIPITATION TO MEET THE WATER REQUIREMENT OF CROPS

FIG. 5.1 OPTIMAL POLICIES

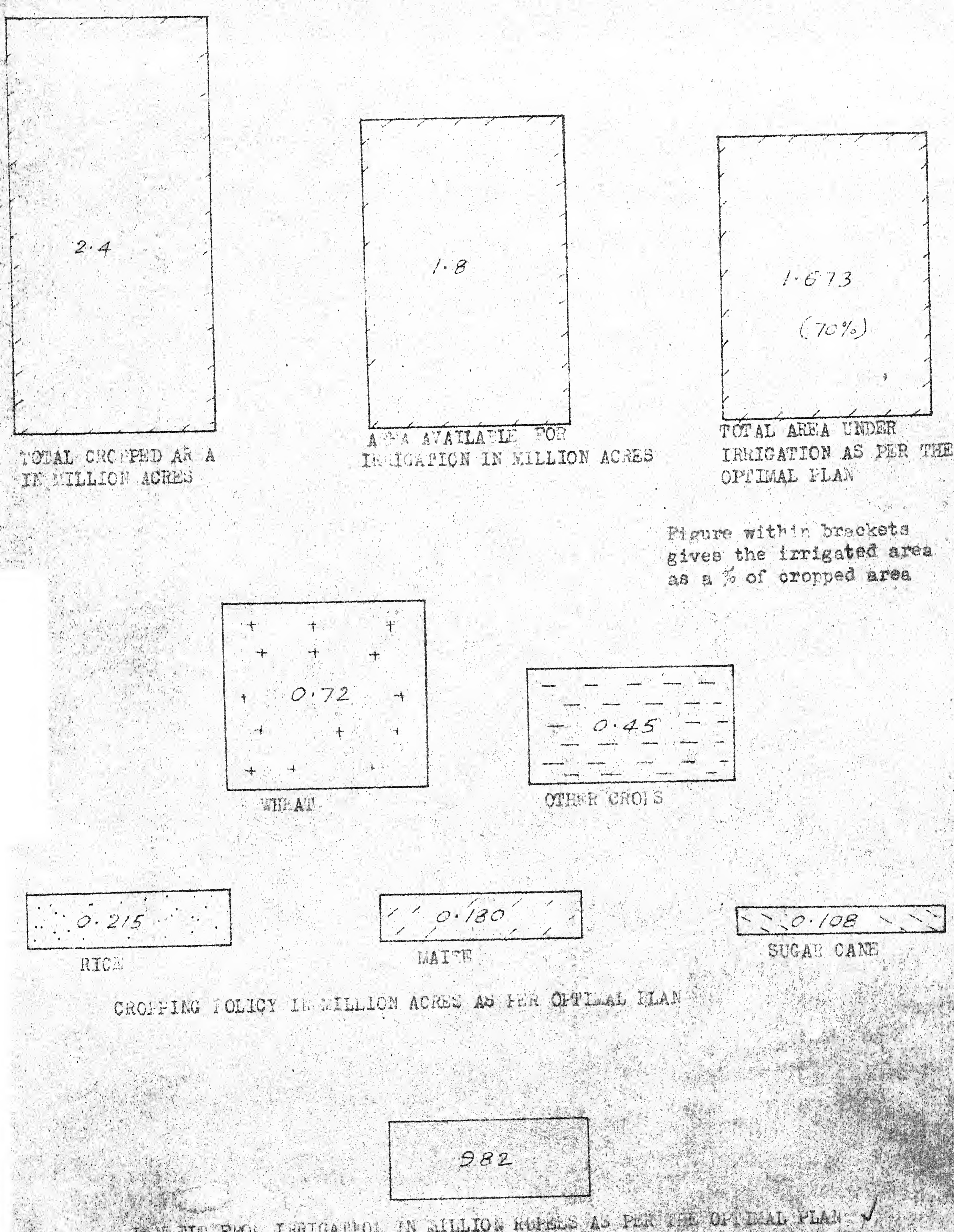


FIG. 5.2 OPTIMAL POLICIES

Simplex alogrithm was used to determine the optimal policy. Each run of the Linear Program where the Simplex tableau was generated as a single array matrix from the required hydrologic, geohydrologic and economic data fed, took about 4 minutes of IBM/7044/1401 computer time to reach the optimal solution.

5.2 OPTIMAL POLICIES:

The results of the optimal policy arrived at are given in Figures 5.1 and 5.2.

5.2.1 Optimal Water Releases:

As would be expected from the prevailing comparative costs of canal and tube-well waters, we find from figure 45.1 that canals are used to maximum capacity of 202 thousand acre feet in all the months where water release for irrigation is required. We also find that tube-wells are used to full capacity of 404 thousand acre-feet in the month of October and in all other months when operated, at varying amounts, all less than this value. In the monsoon months of July, August and September we find that all the water

requirements are met by natural precipitation alone. Figure 5.1 also gives the net water made available for irrigation after abstraction of all forms of losses considered in the model.

5.2.2 Optimal Cropping Policy:

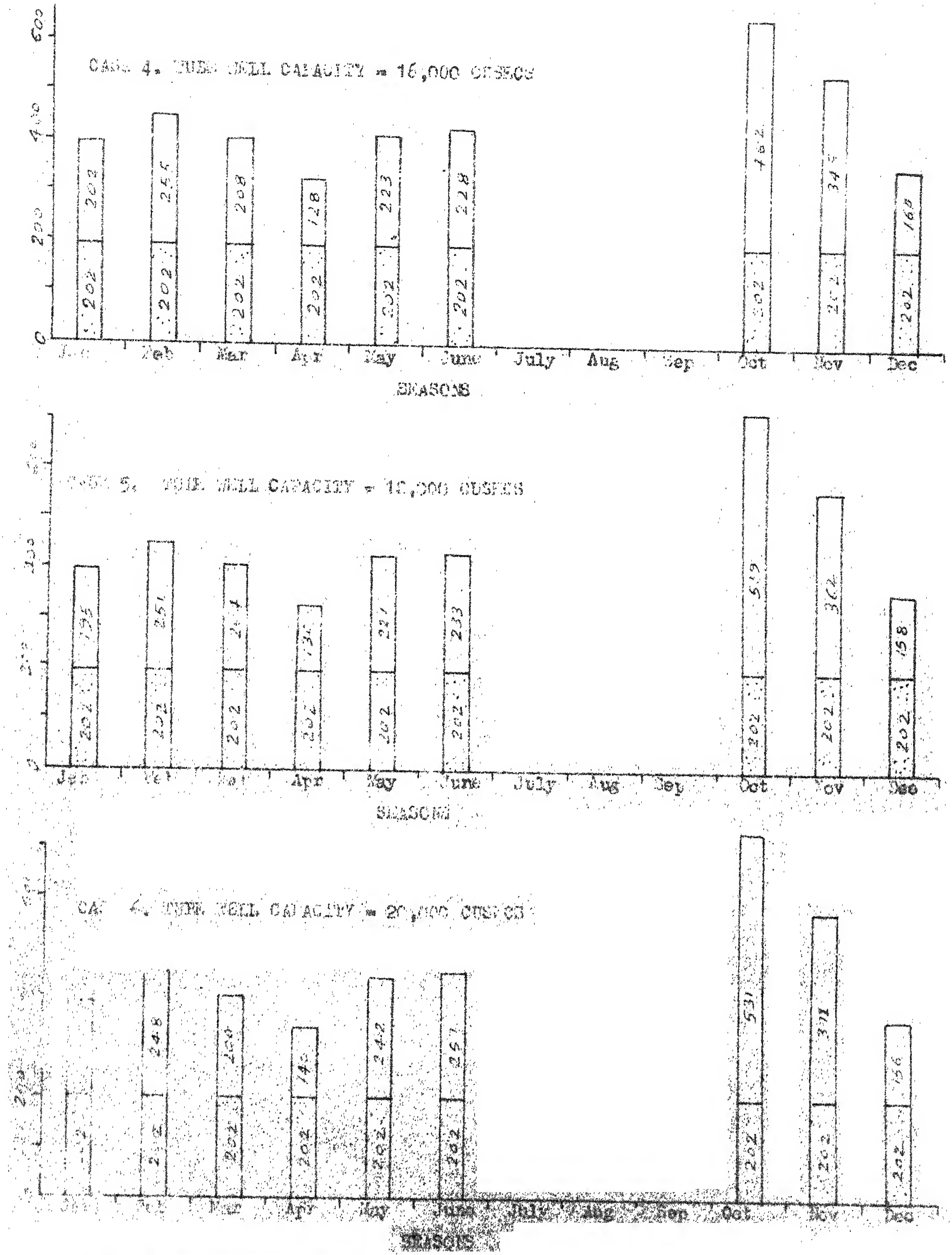
Figure 5.2 gives the optimal acreages of irrigated area under each of the 6 crops we considered in the model. While wheat, maize, sugar-cane and other crops enter the solution at their maximum specified acreages, rice centers the solution at a level of 0.215 million acres, which is less than the maximum specified level of 0.288 million acres and cotton does not enter the solution at all.

5.2.2 Total Benefits:

The total benefits accrued from the irrigation activity as per the optimal plan is 982 million rupees.

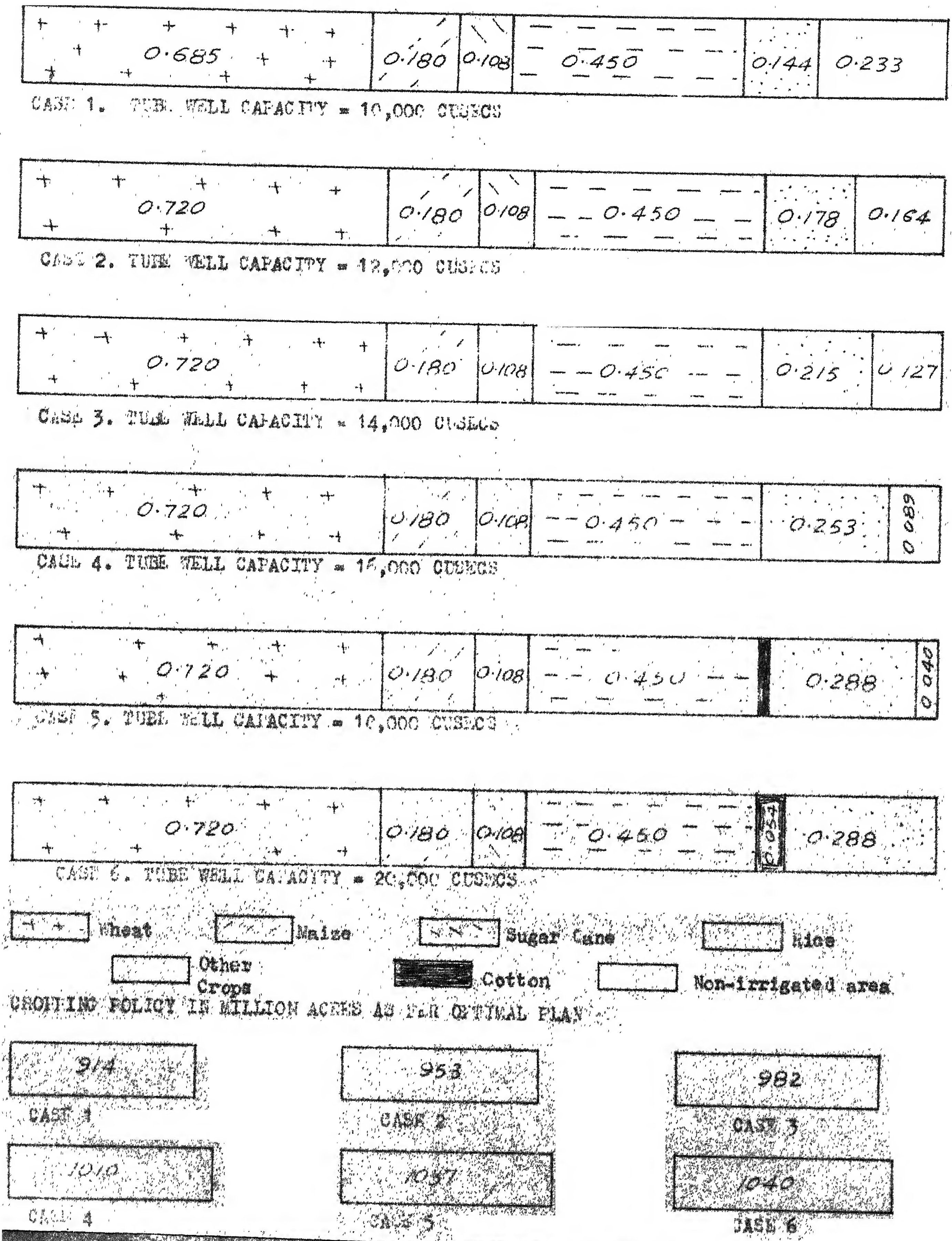
5.3 SENSITIVITY ANALYSIS:

The linear programming model also provides information about the sensitivity of the results to



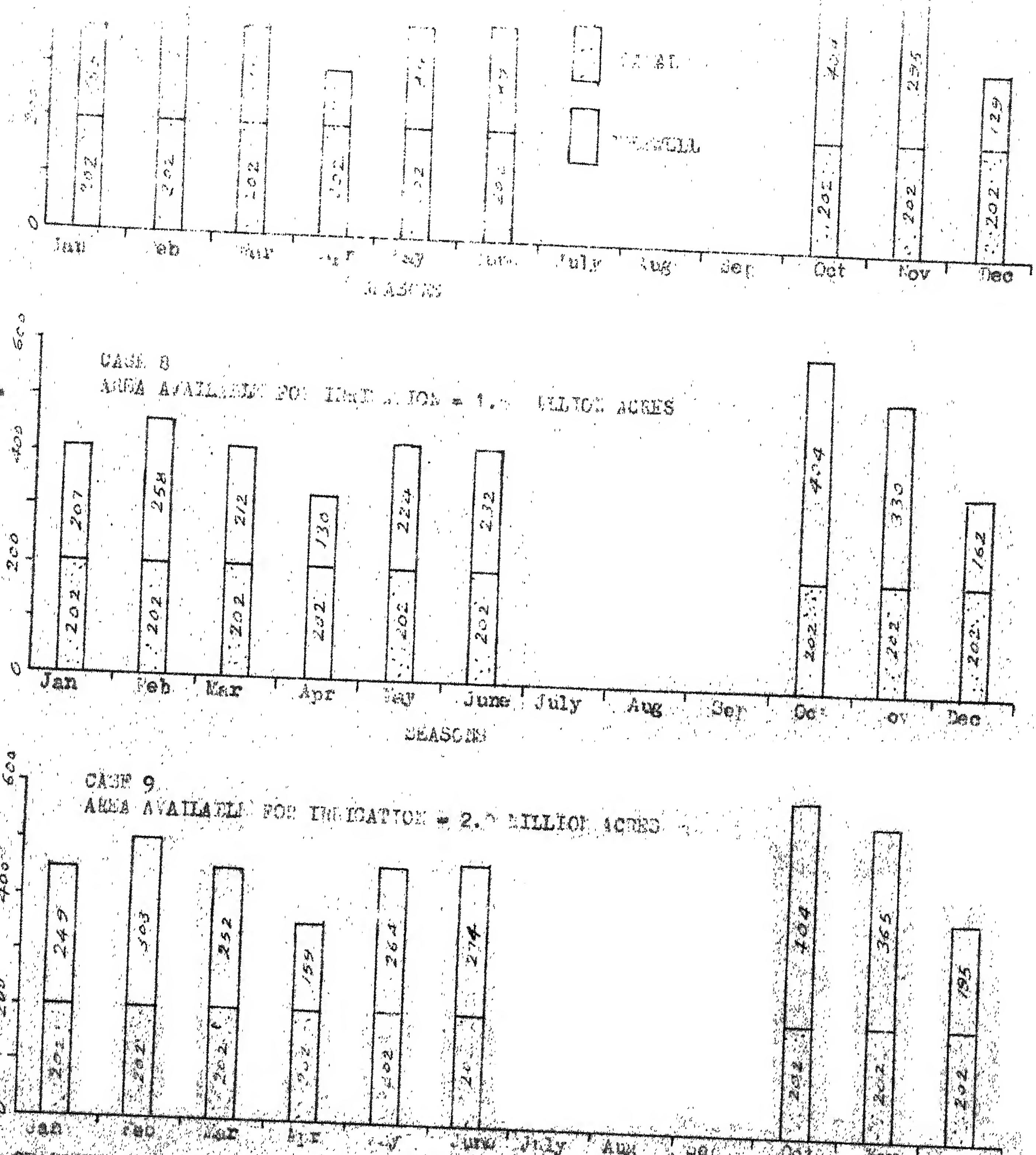
[illegible] OPTIMAL PLAN

FIG. 5.3 SENSITIVITY ANALYSIS ON TUBE WELL CAPACITY



REVENUE FROM IRRIGATION IN MILLION RUPEES AS PER OPTIMAL PLAN

FIG. 5.3 SENSITIVITY ANALYSIS OF TUBE WELL CAPACITY



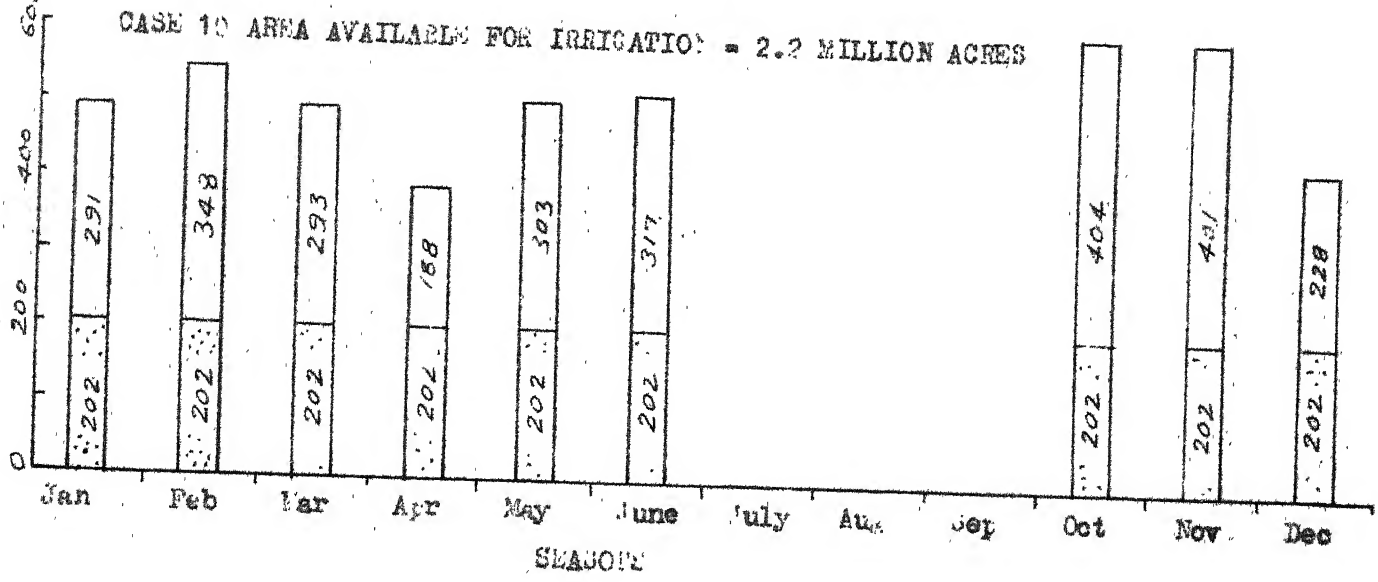
SEASONAL RELEASES FROM CANALS AND TUBE WELLS IN THOUSAND ACRE-FEET AS PER OPTIMAL PLAN

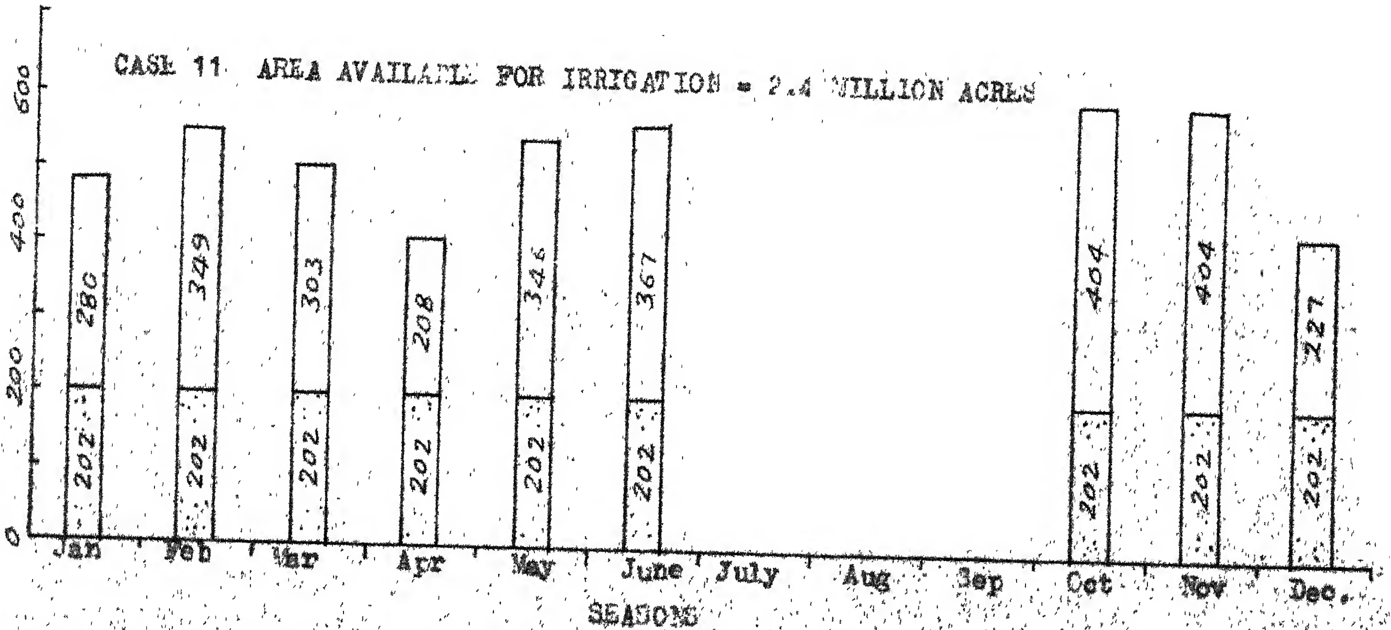
FIG 5.4 SENSITIVITY ANALYSIS ON AREA AVAILABLE FOR IRRIGATION

errors in estimation of the input data. Sensitivity analysis were carried out on the tube-well capacity, on the area available for irrigation, on the operations costs for canals and tube wells and on the values per pound of the crops considered. Results of the sensitivity analysis are reported in Figures 5.3 to 5.6.

5.3.1 Sensitivity Analysis on Canal Capacity:

Figure 5.3 reports the changes in the optimal solution over a range of canal capacities. For all the cases considered we find that there is no change in the canal releases. A significant increase in the tubewell release with increase in tube well capacity is also found only in the months of October and November. Wheat, maize, sugar-cane and other crops enter the solution at their maximum specified level in the model at a canal capacity of 12,000 cusecs and with increased capacity of tubewells thereafter, they show no change. Increased canal capacity from 12,000 cusecs onwards only forces more and more irrigated area under rice to enter the



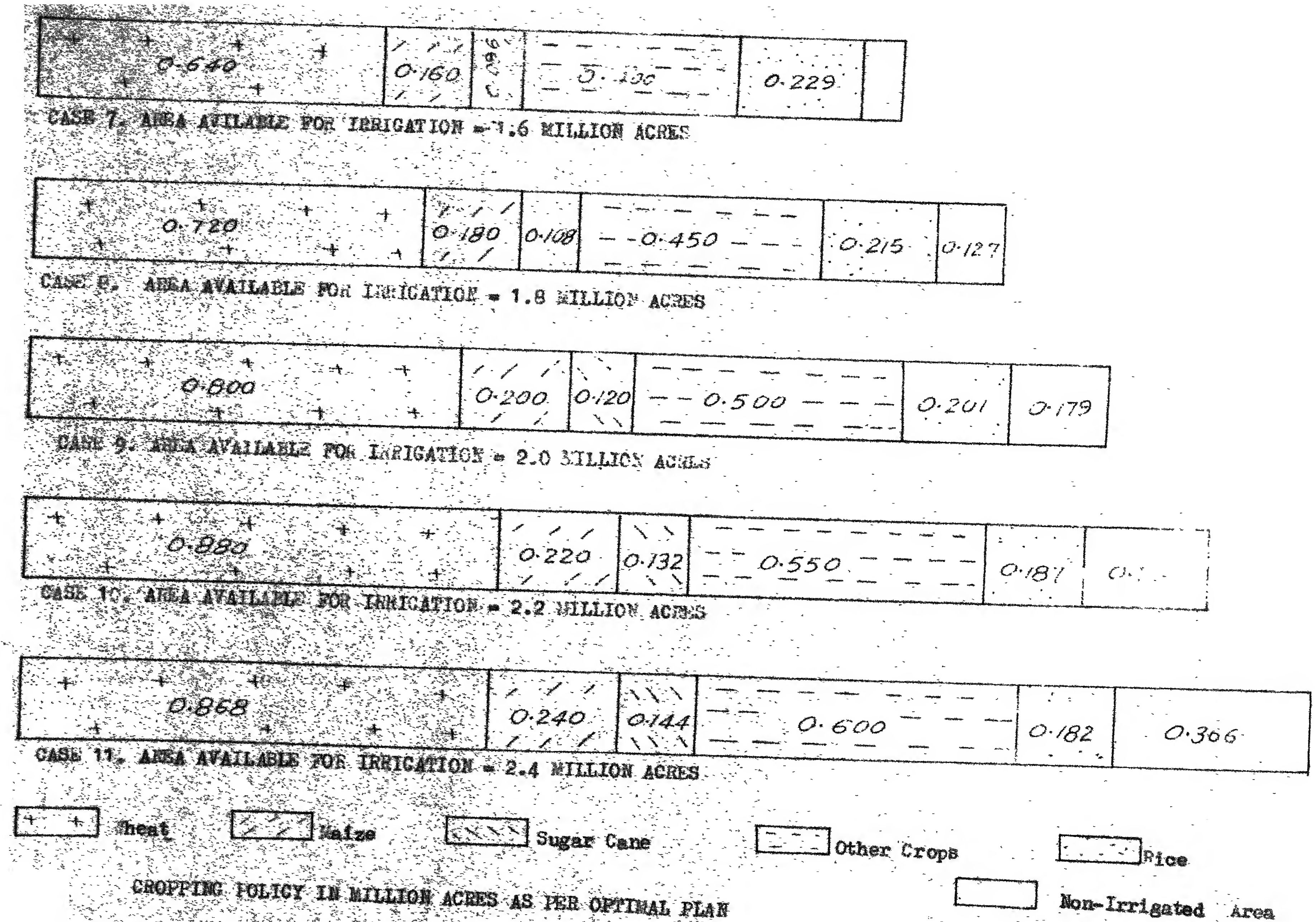


SEASONAL WATER RELEASES FROM CANALS AND TUBE WELLS IN THOUSAND ACRE-FEET AS PER OPTIMAL PLAN

Case 7	Case 8	Case 9	Case 10	Case 11
903	982	1061	1140	1191

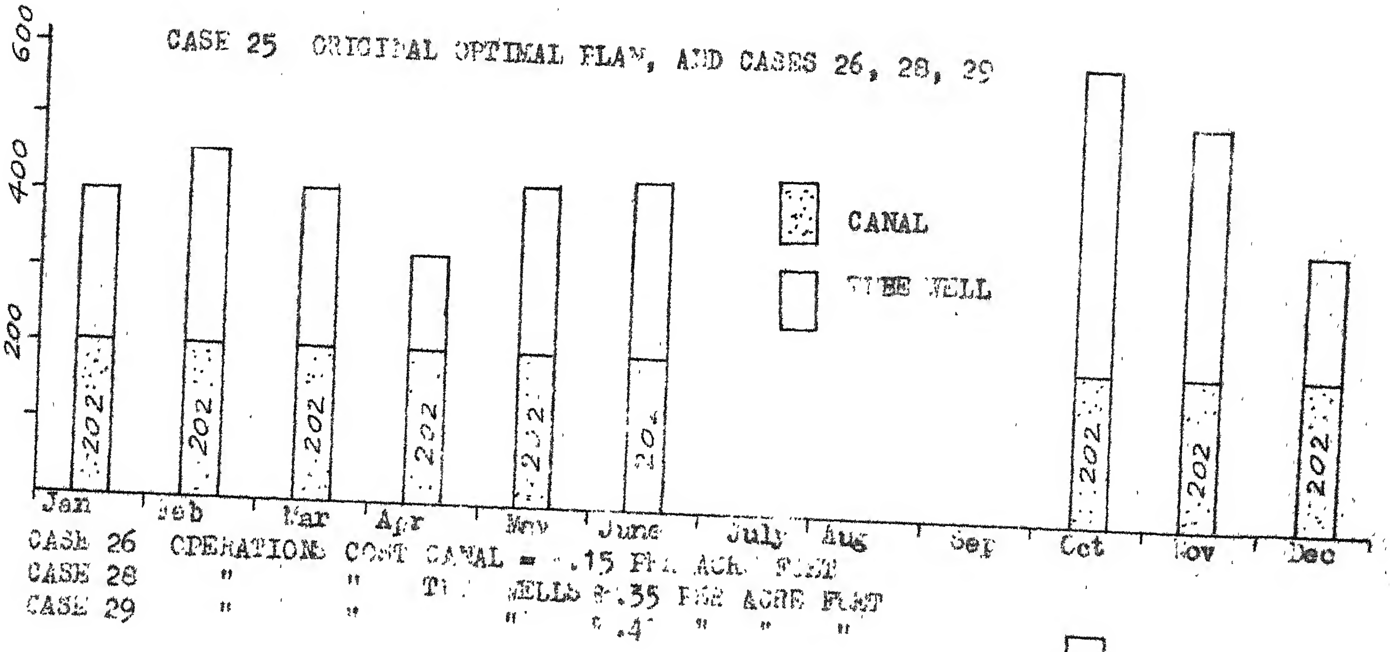
BENEFITS FROM IRRIGATION IN MILLION RUPEES AS PER OPTIMAL PLAN

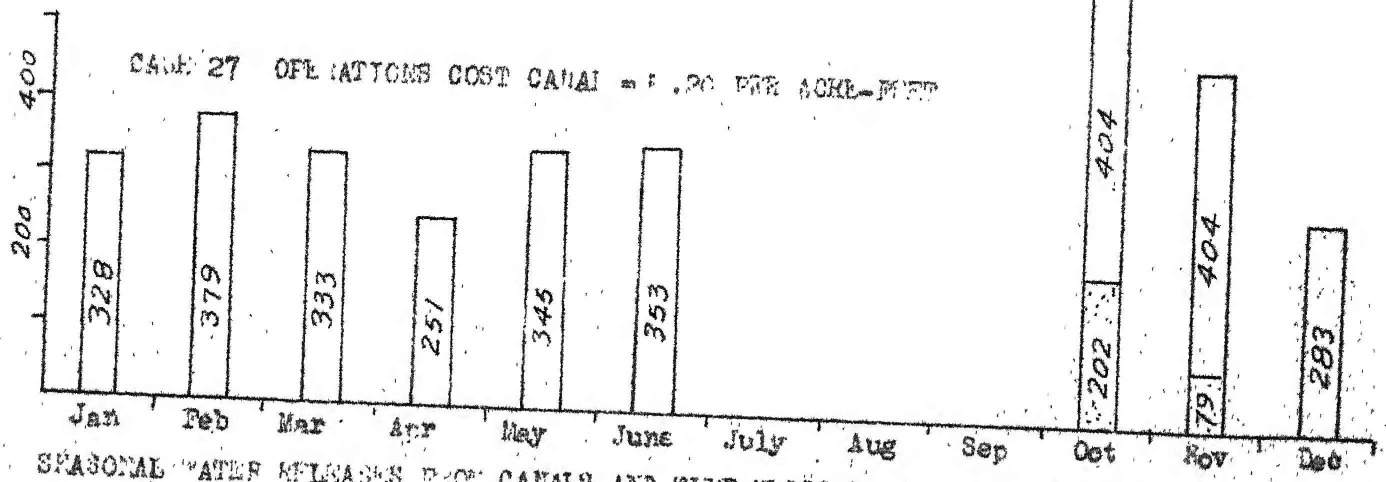
FIG. 5.4 SENSITIVITY ANALYSIS ON AREA AVAILABLE FOR IRRIGATION



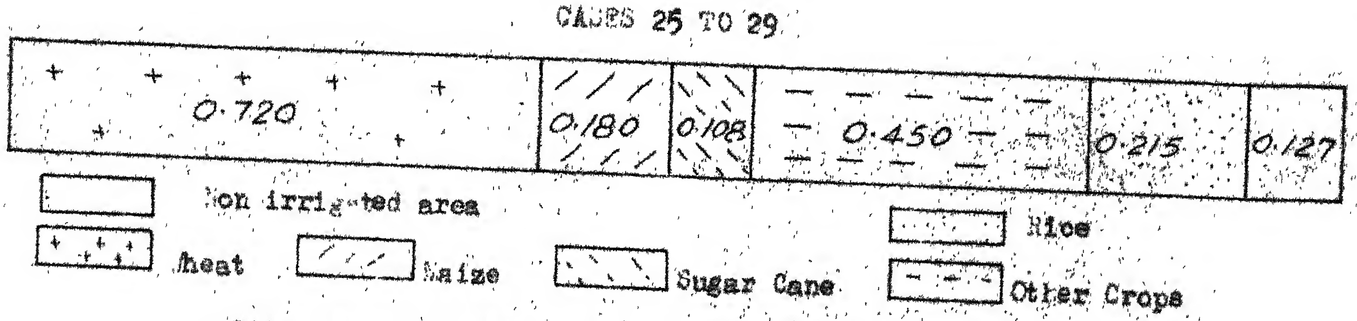
CROPPING POLICY IN MILLION ACRES AS PER OPTIMAL PLAN

FIG. 5.4 SENSITIVITY ANALYSIS ON AREA AVAILABLE FOR IRRIGATION

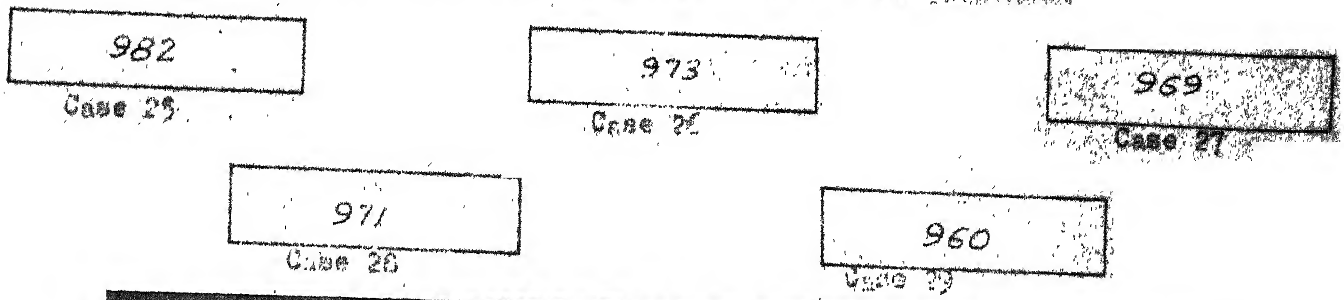




SEASONAL WATER RELEASES FROM CANALS AND TUBE WELLS IN THOUSAND ACRE-FEET AS PER OPTIMAL PLAN



CROPPING POLICY IN MILLION ACRES AS PER OPTIMAL PLAN



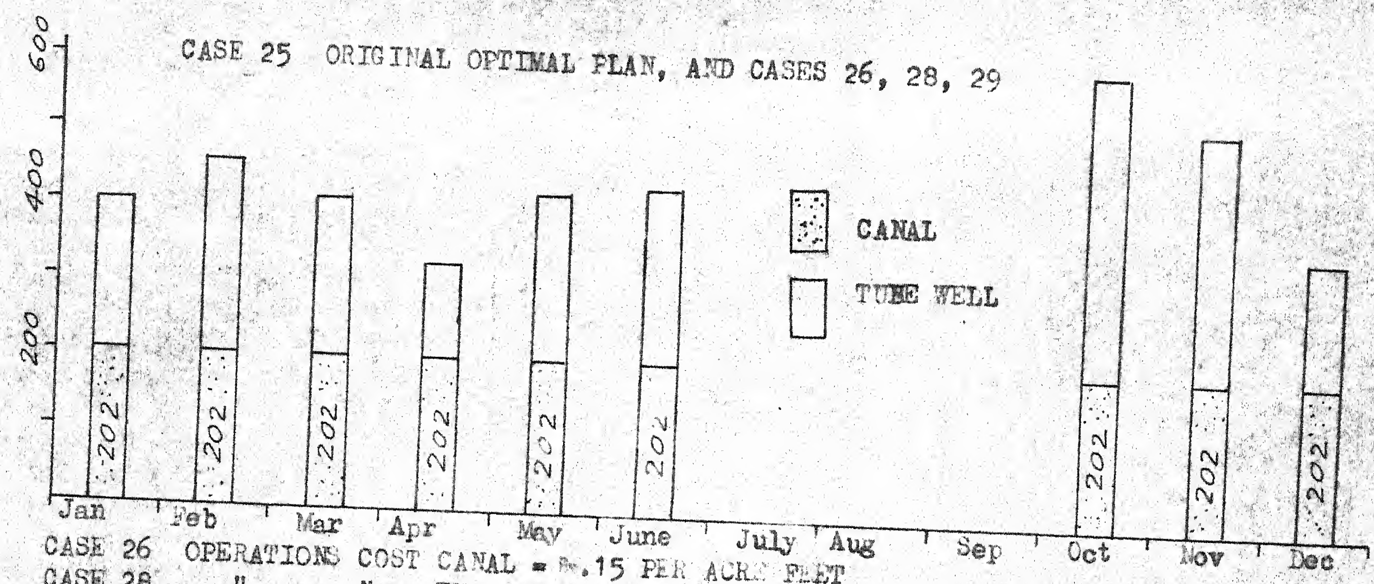
BENEFITS IN MILLION RUPEES AS PER OPTIMAL PLAN

FIG. 5.4 SENSITIVITY ANALYSIS ON OPERATIONS COSTS FOR CANALS AND TUBE WELLS

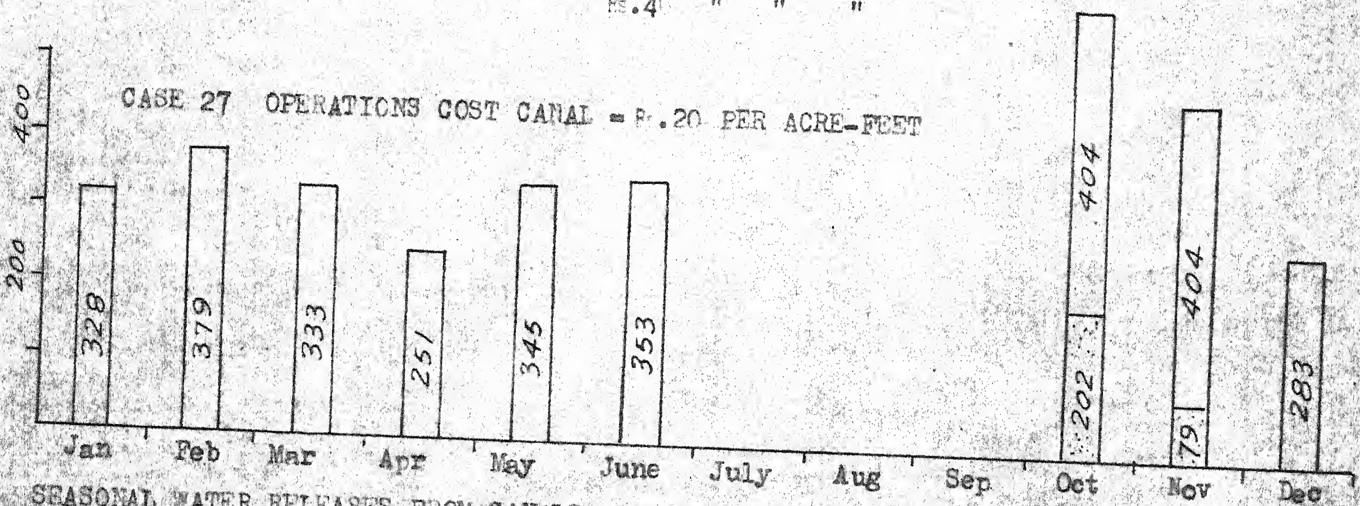
solution. At a tubewell capacity of 18,000 cusecs rice enters the solution at its maximum specified level of 0.288 million acres, and cotton also enters the solution at a level of 0.014 million acres. At a canal capacity of 20,000 cusecs, cotton also enters the solution at its full specified level and the entire area of 1.8 million acres available for irrigation is irrigated. As can be expected, the benefits increase with increase in tubewell capacity and are all shown in Figure 5.5 The marginal benefit for an increased capacity of 2000 cusecs is steady at 28 million rupees in the range considered.

5.3.2 Sensitivity Analysis on Area Available For Irrigatiom:

Fig. 5.4 reports the changes in optimal solution over a range of area available for irrigation. For all the cases considered we find that there is no change in the canal releases. With increased areas available for irrigation, the tube-well releases exhibit an increase in level and at a level of 2.4 million acres, incidently the total cropped area in the region, the tube-well is used to full capacity also in the month of November. In all

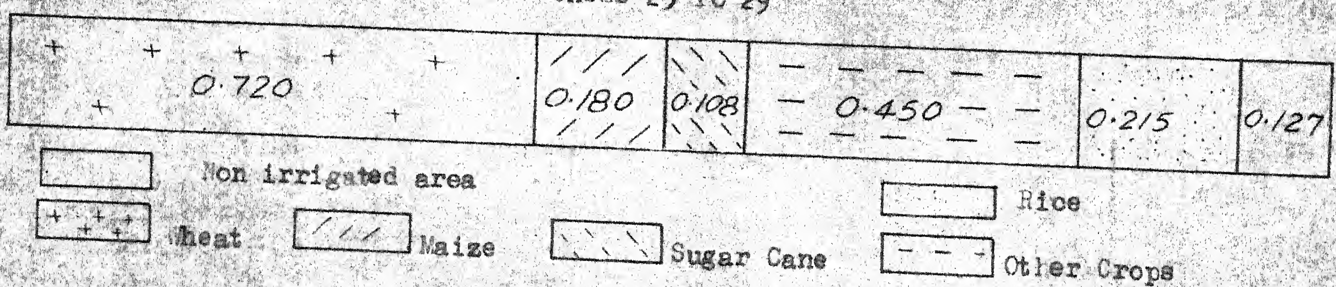


CASE 26 OPERATIONS COST CANAL = Rs.15 PER ACRE FEET
CASE 28 " " TUBE WELLS Rs.35 PER ACRE FEET
CASE 29 " " " Rs.40 " " "



SEASONAL WATER RELEASES FROM CANALS AND TUBE WELLS IN THOUSAND ACRE-FEET AS PER OPTIMAL PLAN

CASES 25 TO 29



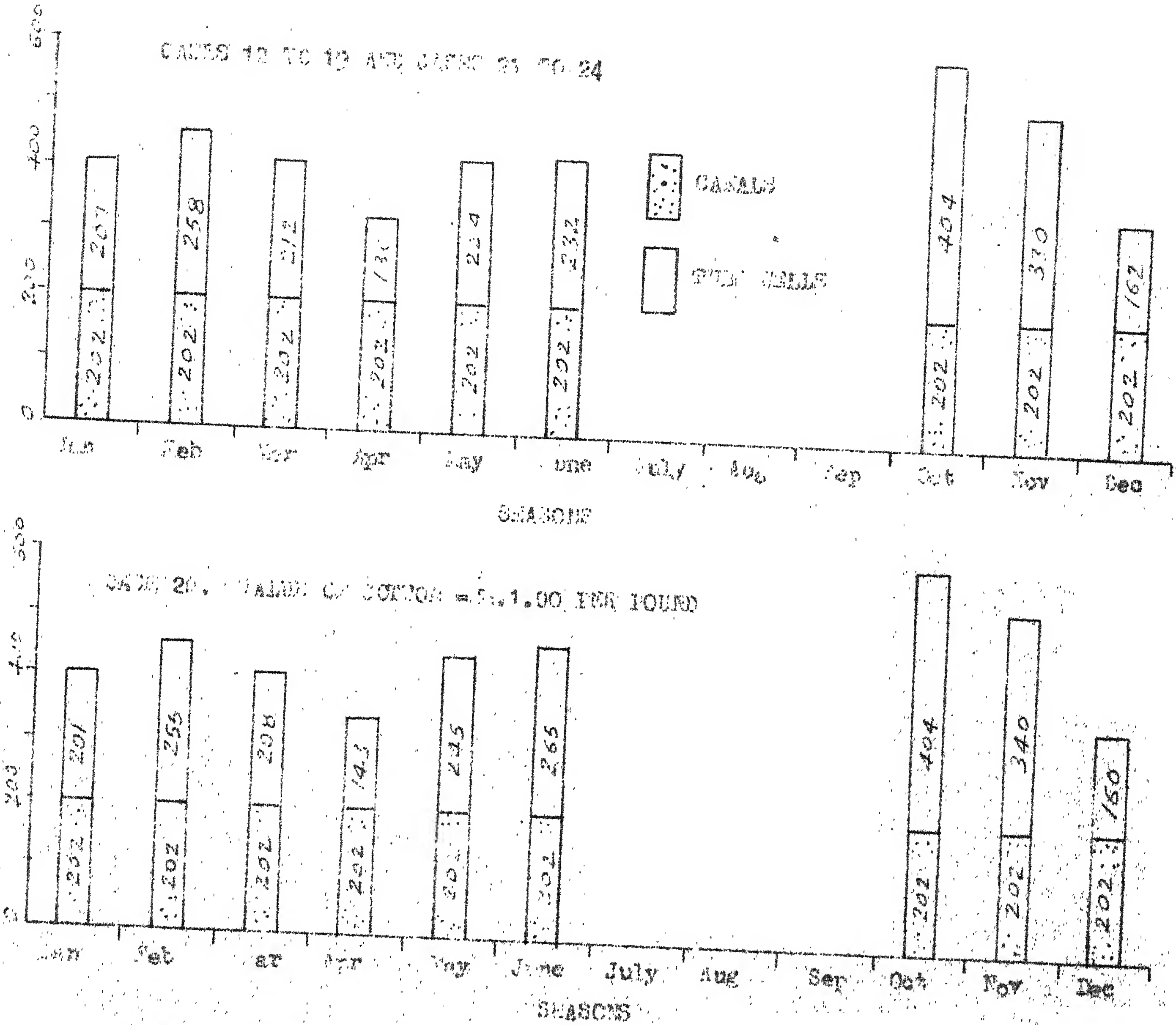
CROPPING POLICY IN MILLION ACRES AS PER OPTIMAL PLAN

982	973	969
Case 25	Case 26	Case 27
971	960	
Case 28	Case 29	

the cases considered we find that maize, sugar-cane and other crops enter the solution at their maximum level specified in the model. In the case of wheat it enters the solution at its maximum specified level upto 2.2 million acres being made available for irrigation. At a level of 2.4 million acres there is a drop in the irrigated area under wheat as compared to the level of 2.2 million acres. In the case of rice there is a progressive reduction in irrigated area with increase in area available for irrigation. In all the cases considered cotton does not enter the solution at all. There is an increase in the benefits from irrigation activity with increase in area available for irrigation implying an under utilization of available waters at lower levels of areas made available for irrigation.

5.3.3 Sensitivity Analysis on Operations Costs For Canal and Tubewells

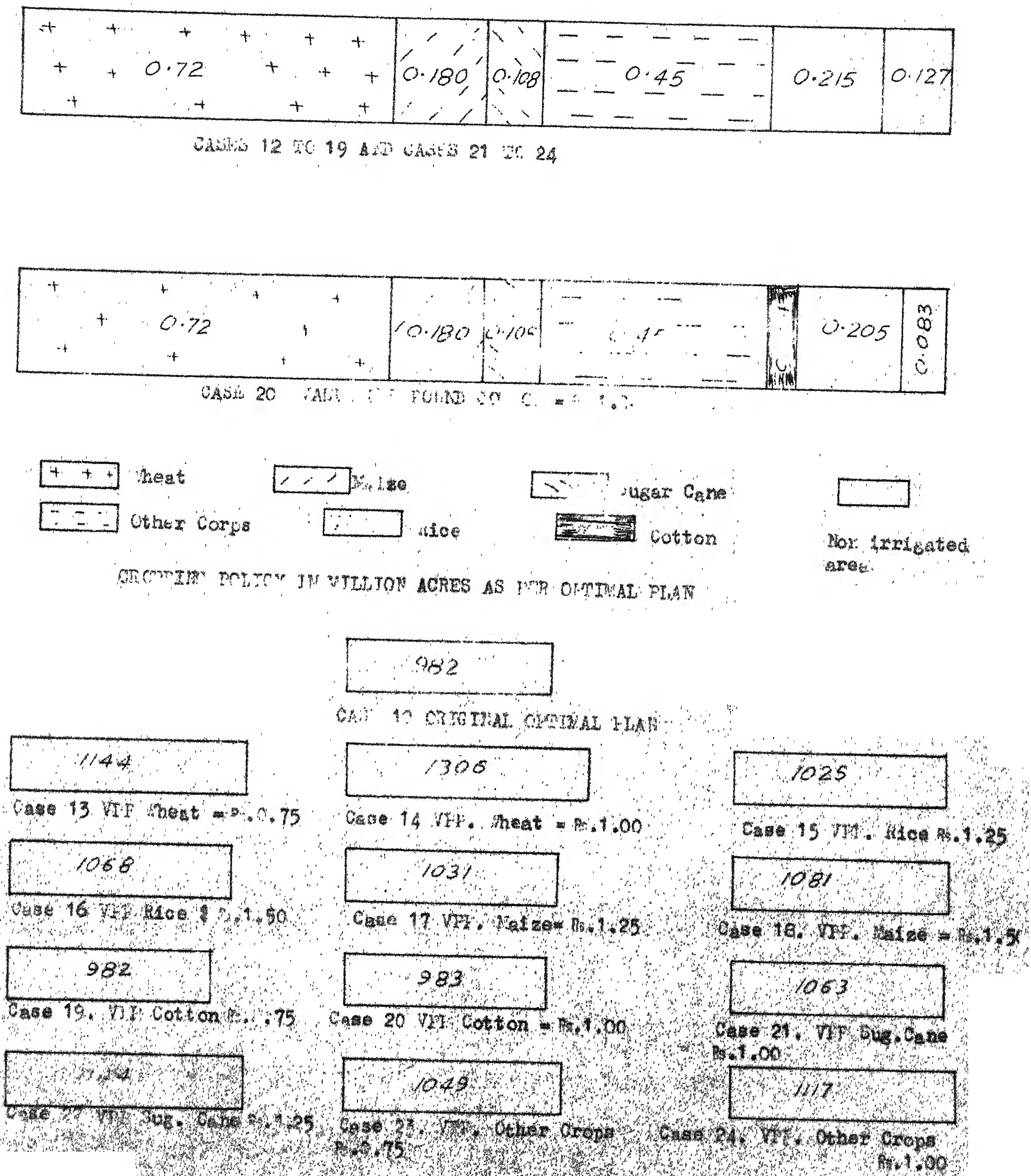
Figure 5.5 reports the changes in optimal solution for a range of operations costs for canals and tubewells keeping all other parameters same. For operations costs for canals at Rs. 10 and Rs. 15



CASE 12. ORIGINAL OPTIMAL PLAN
CASE 13. VPP WHEAT = Rs.0.75, CASE 14. VPP WHEAT = Rs.1.00
CASE 15. VPP RICE = Rs.0.25, CASE 16. VPP RICE = Rs.1.25
CASE 17. VPP MAIZE = Rs.1.25, CASE 18 VPP MAIZE = Rs.1.25
CASE 19. VPP COTTON = Rs.0.75 CASE 20 VPP COTTON Rs.1.00
CASE 21 VPP SUGARCANE = Rs.1.00; CASE 22 VPP SUGARCANE Rs.1.25
CASE 23. VPP OTHER CROPS = Rs.0.75, CASE 24 VPP OTHER CROPS Rs.1.00
VPP = VALUE PER POUND

SEASONAL WATER RELEASES FROM CANALS AND TUBE WELLS IN THOUSAND ACRE-FEET AS PER OPTIMAL PLAN

FIG. 5.6 SENSITIVITY ANALYSIS OF VALUE OF CROPS



BENEFITS IN MILLION RUPEES AS PER OPTIMAL PLAN

FIG. 5.6 SENSITIVITY ANALYSIS ON VALUE OF CROPS

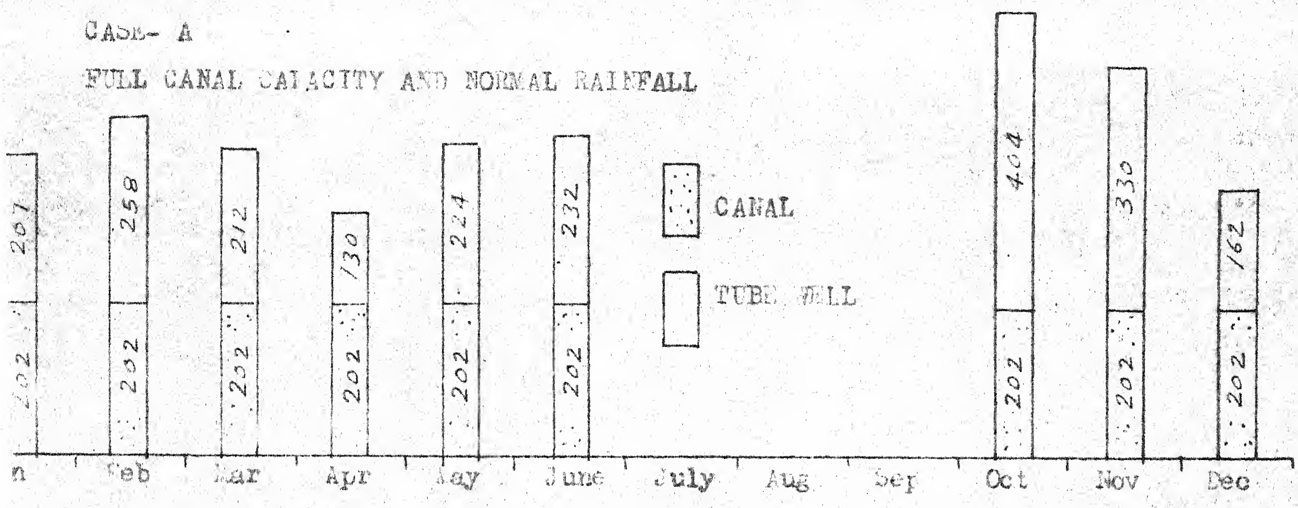
per acre-feet and for all the operations costs for tube-wells considered we find that there is no change in the water release policy. When the canal operations costs is Rs. 20 per acre-feet we find that the releases from canal enter the solution only in the months of October in its full capacity and in November. For the same case, we find a marked increase in the tube-well releases during all the months. For all the cases considered there is no change in the optimal cropping policy. As can be expected, the benefits show a decline with increased operations costs.

5.3.4 Sensitivity Analysis For Value of Crops:

Figure 5.6 reports the changes in optimal solution for a range of values of individual crops with all other parameters remaining the same. For all the cases considered for wheat, maize rice and sugar cane and other crops we find that there is no change in the water releases policy. For the case when the value of cotton is Rs. 1.00 per pound we find that there is a difference but not a significant one for the tube-well releases while there is no change in the canal release. For the same case we also find

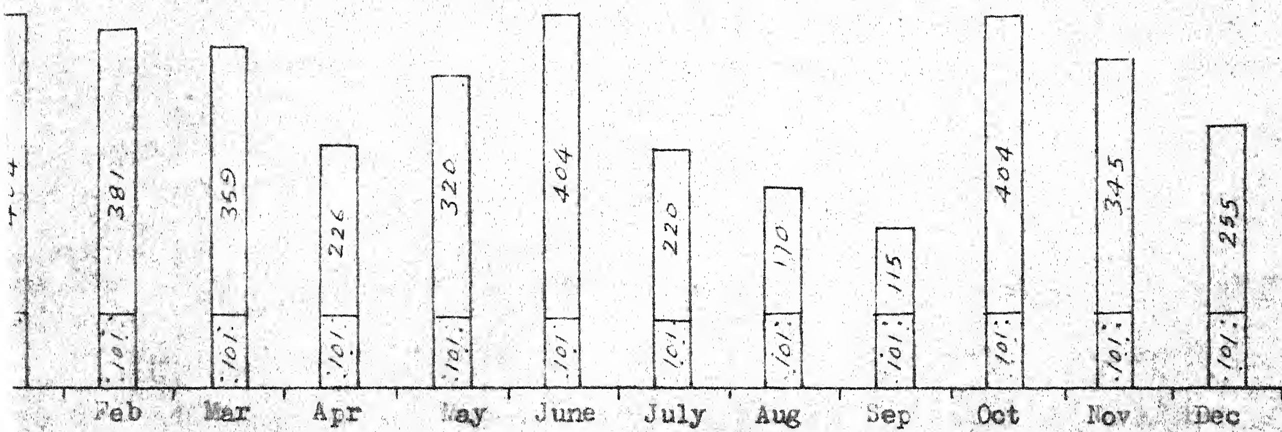
CASE- A

FULL CANAL CAPACITY AND NORMAL RAINFALL



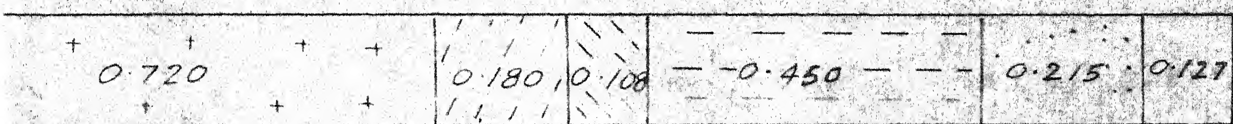
CASE- B

CANAL CAPACITY REDUCED TO HALF AND RAINFALL 1/4TH THE NORMAL

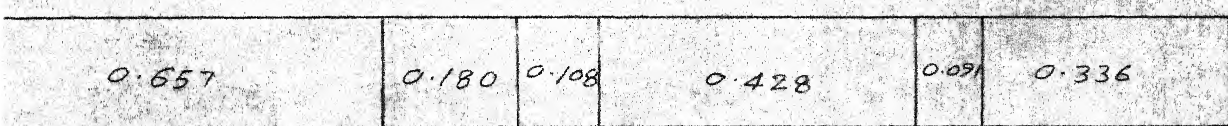


SEASONS

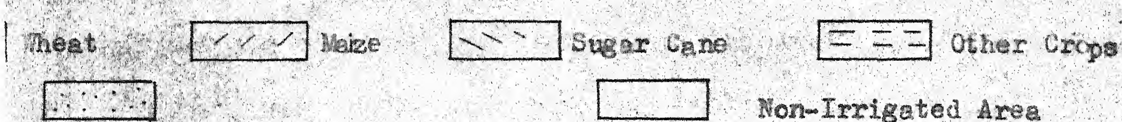
SEASONAL RELEASES FROM CANALS AND TUBEWELLS IN THOUSAND ACRE-FEET AS PER OPTIMAL PLAN



CASE- A



CASE - B



CROPPING POLICY IN MILLION ACRES AS PER OPTIMAL PLAN

that cotton enters the solution at its maximum specified level of 0.054 million acres and this is at the cost of rice whose irrigated area drops to 0.205 million acres. For all other cases there is no change in the cropping policy. As can be expected, with increase in value of crops, there is an increase in the total benefits.

5.4 CASE OF RAINFALL BEING ONE FOURTH OF NORMAL RAINFALL:

A case where the rainfall is assumed to be one fourth of the normal rainfall used in the model was also considered. For this case it was also assumed that the canal can be used only up to half its capacity we had considered in the model. The results of optimal solution for this case is reported in Fig. 5.7. We find that the canal is used to available capacity of 10 thousand acre-feet in all the months of the year. Of significanee is the appearance of canal releases man-soon months of July, August and September. Tube-well releases also appear in all the months and the maximum capacity of 404 thousand acre-feet is used in the months of January, June and October. For all other months

tube well releases are found to be greater than in the original optimal plan. While irrigated areas of maize, sugar cane and other crops show no change in this case as compared to the original plan, we find that for this case, there is a reduction in the areas under irrigation of wheet and rice. As can be expected, there is also a reduction in the total benefits for this case as compared to the original optimal plan.

5.5 CONCLUSIONS AND SCOPE OF FURTHER STUDIES

For a set of deterministic input data we had formulated a Linear Programming Model which gives the water releases from two sources, canals and tube wells, to meet the water requirement of crops and the extent of irrigated acreages under each of the crop considered, so that the returns from irrigation activity is maximized subject to a set of constraints. This model was applied to the Bari Doab Tract in Punjab and the optimal solutions have been reported in the preceeding sections of this chapter.

What strikes one at the first glance of the optimal solutions presented is the absence of releases from tube-wells direct in to drainage system although

this was included in the model. One can easily explain it by the presence in the model of only a cost factor for this release and no benefit factor. While planning the optimal policy for a broader basin, say the whole of Punjab State, a benefit factor will get introduced for these releases since they can be made use of for irrigation in the lower regions. This would force their entry into the optimal solution. Another method, not considered in the model we had developed, to force their entry into the optimal solution would be to impose a minimum constraint on the amount of water to be pumped out of the aquifer in a year of operation. This would call for a comprehensive data on the ground water balance.

In the sensitivity analysis carried out for the area available for irrigation, we found that with increase in area available, there is a reduction of irrigated area for rice and wheat in the optimal plan. Again this was more pronounced in the case of rice. This is because the model we formulated does not include a minimum constraint for the irrigated area of individual crops. With the current accent on increased food grains production, it would be necessary

to include in the model minimum constraints for the irrigated acreages of these two crops. This would however call for a comprehensive demand function for these crops.

None can fail to notice that cotton does not enter the solution of the optimal plan, the reason being absence of minimum constraint for irrigated areas of different crops in the model we formulated. This however does not assume much importance because if the past trend is any indication there has been a progressive reduction in the cropped area of cotton in the region of our study.

The model we formulated had all input data as deterministic in nature, this,not truely reflecting the stochastic character of river inflows and natural precipitation. For more realistic picture it would become necessary in future studies to incorporate the stochastic character of these variables.

Another extension would be to include a constraint on the quality impairment. This constraint would hold the annual quality detirioration of ground water to a certain level.

Another extension would be to include a surface reservoir upstream of the canal head work. For the region of our study this assumes importance with the Thien Dam coming up across the Ravi river in Himachal Pradesh.

APPENDIX - A

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APPENDIX - B

COMPUTER PROGRAM

```
$IBJOB
$IBFTC MAIN
C       IN THE MAIN PROGRAM THE SIMPLEX TABLEAU IS GENERATED AS
C       A SINGLE ARRAY MATRIX COLUMNWISE
C       AND THE OPTIMAL SOLUTION IS OBTAINED IN THE SAME STORAGE LOCATION
C       N  IS NUMBER OF VARIABLES TO BE DETERMINED IN THE OBJECTIVE
C       FUNCTION
C       M1  IS NUMBER OF CONSTRAINT EQUATIONS OF THE TYPE LESS
C       THAN OR EQAL TO 0
C       ZS=1  SS=M1+1  IPR1=N  IPR2=M1  JL1=N  JL2=M1
C       NOC=NUMBER OF CROPS   NOS=NUMBER OF SEASONS
C       RIVROF(I)=RIVER RUNOFF IN ACRE-FEET IN SEASON I
C       PI(I)=RAINFALL IN INCHES IN SEASON I
C       WR(I,J)=WATER REQUIREMENT IN INCHES OF CROP J IN SEASON I
C       YLDPA(J)=YIELDIN POUNDS PER ACRE OF CROP J
C       VALPP(J)=VALUE IN RUPEES PER POUND OF CROP J
C       CAPC,CAPT,CAPD ARE CAPACITIES OF CANAL,TUBE-WELL,AND
C       DRAINAGE IN CUSECS
C       OCC,OCT,AND OCD ARE OPERATIONS COST OF CANALS, TUBE WELLS,
C       AND DRAINAGE IN RUPEES PER ACRE-FEET
C       SR, AR, ET ARE FRACTIONS OF WATER LOST AS SURFACE RUNOFF , AQUIFER
C       RECHARGE, AND NON-BENEFISIAL EVAPOTRANSPIRATION RESPECTIVELY
C       AET, AAR, ARF  ARE ANNUAL AQUIFER EVAPORATION, ANNUAL AQUIFER
C       RECHARGE FROM ADJOINING AQUIFERS, AND ANNUAL AQUIFER RETURN
C       FLOW RESPECTIVELY
C       EFC, EFT, EFD ARE EFFICIENCIES OF CANALS, TUBE-WELLS AND DRAINAGE
C       RPTADC, RPTADT, AND RPTADD ARE RATIO OF PEAK TO AVARAGE DEMAND OF
C       CANALS , TUBE_WELLS, AND DRAINAGE
C       DAYSC, DAYST, DAYSD ARE NUMBER OF DAYS CANALS, TUBE-WELLS,
C       AND DRAINAGE ARE OPERATED IN A SEASON
C       PMR IS PERMISSIBLE MINING RATE IN ACRE_FEET PER YEAR FROM AQUIFER
C       TOTA IS TOTAL CROPPED AREA
C       TIA IS TOTAL AREA AVAILABLE FOR IRRIGATION
C       PERAR(J) IS FRACTION OF TOTAL AREA AVAILABLE FOR IRRIGATION
C       MADE AVAILABLE FOR CROP J
C       ANEW IS CONVERSION FACTOR FOR ACRE_FEET PER DAY TO CUSECS
        DIMENSIONPR1(100),PR2(100),L1(100),L2(100)
        DIMENSION RIVROF(12),PI(12),WR(6,12),VALPP(6),YLDPA(6),UPIA(12)
        DIMENSION  PERAR(6)
        COMMONA(3500)
        INTEGER ZS,SS,V,R,S,PR1,PR2,FALL
        REAL MAX
```

```
      READ50,ZS,SS,N,M1
50    FORMAT(4I5)
      READ 69,IPR1,IPR2,JL1,JL2
69    FORMAT(4I5)
      READ70,NOS,NOC
70    FORMAT(2I5)
      READ 71,(RIVROF(IA),IA=1,NOS)
      READ 71,(PI(IA),IA=1,NOS)
      READ71,((WR(JO,KO),KO=1,NOS),JO=1,NOC)
      READ 71,(YLDPA(JP),JP=1,NOC)
      READ71,(VALPP(JP),JP=1,NOC)
      READ 71,CAPC,CAPT,CAPD,OCC,OCT,OCD
      READ71,(PERAR(I),I=1,NOC)
71    FORMAT(6F10.2)
      READ 72,SR1,AR1,ET1
       READ 72,SR2,AR2,ET2
      READ 72,SR3,AR3,ET3
      READ 72,AET,AAR,ARF
      READ 72,EFC,EFT,EFD
      READ 72,RPTADC,RPTADT,RPTADD
      READ 72,DAYSC,DAYST,DAYSD
72    FORMAT(3F10.2)
      READ 73,PMR
73    FORMAT(F10.1)
      READ74,TIA,TOTA
74    FORMAT(2F10.1)
      ANEW=4840.0*9.0/(24.0*60.0*60.0)
      CONC=RPTADC*ANEW/(DAYSC*EFC)
      CONT=RPTADT*ANEW/(DAYST*EFT)
      COND=RPTADD*ANEW/(DAYSD*EFD)
      THETA1=1.0-SR1-AR1-ET1
      THETA2=1.0-SR2-AR2-ET2
      COND1=COND*(SR1+SR2*THETA1)
      COND2=COND*SR2
      TAPI=0.0
      DO75I=1,NOS
75    TAPI=TAPI+PI(I)/12.0
      A(1)=0.0
      DO131I=1,NOS
      IR1=I+1
131   A(IR1)=RIVROF(I) * 10.0 ** 6
      DO132I=1,NOS
      IR1=IR1+1
132   A(IR1)=CAPC
      DO133I=1,NOS
      IR1=IR1+1
133   A(IR1)=CAPT
```

```
      DO134I=1,NOS
      IR1=IR1+1
134   A(IR1) = CAPD - COND*SR3*TOTA*PI(I)/12.0
      IR1=IR1+1
      A(IR1)=TIA
      IR1=IR1+1
      A(IR1)=PMR+AAR-AET-ARF+TOTA*TAPI*AR3
      DO135I=1,NOS
      IR1=IR1+1
135   A(IR1)=0.0
      DO136I=1,NOC
      IR1=IR1+1
136   A(IR1)=TIA*PEPAR(I)
      DO141J=1,NOC
      IPO=J*SS+1
141   A(IPO)=VALPP(J)*YLDPA(J)
      JX=NOC+1
      JY=NOC+NOS
      DO142J=JX,JY
      KOP=J*SS+1
142   A(KOP)=-(OCC+OCD*(SR1+SR2*THETA1))
      JX=JY+1
      JY=JY+NOS
      DO143J=JX,JY
      KOP=J*SS+1
  143 A(KOP)=-(OCT+OCD*SR2)
      JX=JY+1
      JY=JY+NOS
      DO144J=JX,JY
      KOP=J*SS+1
144   A(KOP)=-(OCT+OCD)
      DO81I=1,NOS
      DO81J=1,N
      IOP=I*ZS+J*SS+1
      IF((J-I).NE.6)GOTO82
      A(IOP)=-1.0
       GOTO81
82    A(IOP)=0.0
81    CONTINUE
      N1=NOS+1
      N2=2*NOS
      DO83I=N1,N2
      DO83J=1,N
      IOP=I*ZS+J*SS+1
      IF((I-J).NE.6)GOTO84
      A(IOP)=-CONC
      GOTO83
84    A(IOP)=0.0
83    CONTINUE
```

```
      N1=N2+1
      N2=3*NOS
      DO85I=N1,N2
      DO85J=1,N
      IOP=I*ZS+J*SS+1
      IF((I-J).NE.6)GOTO86
      A(IOP)=-CONT
      GOTO85
86    IF((J-I).NE.6)GOTO87
      A(IOP)=-CONT
      GOTO85
87    A(IOP)=0.0
85    CONTINUE
      N1=N2+1
      N2=4*NOS
      DO 88 I=N1,N2
      DO 88 J=1,N
      KC=I*ZS+J*SS+1
      IF(J.GT.NOC)GOTO98
      IZ=I-36
      A(KC)=COND*(SR3-SR2)*PI(IZ)/12.0
      GOTO88
98    IF ((I-J).NE.30) GO TO 89
      A(KC)=-COND1
      GO TO 88
89    IF((I-J).NE.18)GOTO90
      A(KC)=-COND2
      GOTO88
90    IF ((I-J).NE.6) GO TO91
      A(KC)=-COND
      GO TO 88
91    A(KC)=0.0
88    CONTINUE
      N1=N2+1
      DO 92 J=1,NOC
      KC=N1*ZS+J*SS+1
92    A(KC)=-1.0
      NS=NOC+1
      DO 93 J=NS,N
      KC=N1*ZS+J*SS+1
93    A(KC)=0.0
      N1=N1+1
      DO 94 J=1,NOC
      KC=N1*ZS+J*SS+1
94    A(KC)=(AR2-AR3)*TAPI
      NS=NOC+1
      NK=NOC+NOS
      DO 95 J=NS,NK
      KC=N1*ZS+J*SS+1
95    A(KC)=AR2*THETA1 +   AR1
```

```
      NY=NK+NOS
      NK=NK+1
      DO 96 J=NK,NY
      KC=N1*ZS+J*SS+1
 96   A(KC)=-(1.-AR2)
      NZ=NY+NOS
      NY=NY+1
      DO 97 J=NY,NZ
      KC=N1*ZS+J*SS+1
 97   A(KC)=-1.0
       N11=N1+1
       N12=N1+NOS
       DO 121  I=N11,N12
       N1Y=I-N1
      DO126 J=1,N
      IAO=I*ZS+J*SS+1
       IF(J.GT.NOC) GO TO 122
      A(IAO)=-WR(J,N1Y)/12.0 + PI(N1Y)*THETA2/12.0
      GOTO126
 122   IF((I-J).NE.44) GO TO 123
       A(IAO)=THETA1*THETA2
      GOTO126
 123   IF((I-J).NE.32) GO TO 124
       A(IAO)=THETA2
      GOTO126
 124   A(IAO)=0.0
126   CONTINUE
 121   CONTINUE
      N11=N12+1
      N12=N12+NOC
      DO127I=N11,N12
      DO128J=1,N
      IAO=I*ZS+J*SS+1
      IF((I-J).EQ.62)GOTO129
      A(IAO)=0.0
      GOTO128
129   A(IAO)=-1.0
128   CONTINUE
127   CONTINUE
      CALL  SIMPLX(ZS,SS,N,M1,FALL,PR1,IPR1,PR2,IPR2,
     1L1,JL1,L2,JL2)
      PRINT1000,A(1)
1000  FORMAT(1X,*TOTAL  BENEFIT =          *,E16.8///)
      DO181I=1,M1
      J=I+1
      PRINT2000,PR2(I),A(J)
181   CONTINUE
2000  FORMAT(1X,I5,*              *,E16.8)
      STOP
      END
```

```
$IBFTC  SIMPLX
C       IN THE PROGRAM THE SIMPLEX TABLEAU IS STORED AS A SINGLE
C       ARRAY MATRIX  COLUMNWISE AND THE OPTIMAL SOLUTION IS OBOA+-E+
C       IN THE SAME STORAGE LOCATION
        SUBROUTINE SIMPLX(ZS,SS,N,M1,FALL,PR1,IPR1,PR2,IPR2,
       1L1,JL1,L2,JL2)
        COMMONA(3000)
        DIMENSION PR1(IPR1),PR2(IPR2),L1(JL1),L2(JL2)
        INTEGER ZS,SS,V,R,S,PR1,PR2,FALL
        REAL MAX
        R=0
        V=-1
        DO 1 K=1,N
        L1(K) = K
    1   PR1(K)=K
        L10 = N
        DO 2 I=1,M1
    2   L2(I) = I
        L20=M1
        DO3I=1,M1
    3   PR2(I)=N+I
        GOTO103
 1021   S=PR1(KP)
        PR1(KP)=PR2(IP)
        PR2(IP)=S
  103   CALL MP7(0,ZS,SS,KP,L1,L10,JL1,MAX)
        IF(MAX.GT.0.)GOTO14
        FALL=0
        RETURN
   14   CALL  MP2(L2,L20,JL2,IP,ZS,SS,KP,Q1,N,V)
  104   IF(IP.NE.0)GOTO15
        FALL=1
        RETURN
   15    CALL  MP3(0,M1,0,N,IP,KP,ZS,SS,1,U)
        GOTO 1021
        END


$IBFTC MP7
C       SUBROUTINE MP7 DETERMINES THE COLUMN THAT ENTERS THE BASIS
        SUBROUTINE MP7(ZNR,ZS,SS,KP,L1,L10,JL1,MAX)
        COMMONA(3000)
        DIMENSIONL1(JL1)
        INTEGER ZNR,ZS,SS
        REAL MAX
        KH=ZNR*ZS+L1(1)*SS+1
        MAX=A(KH)
        KP=L1(1)
        IF(L10.LT.2) RETURN
```

```
      DO1K=2,L10
      KH=ZNR*ZS+L1(K)*SS+1
      IF(A(KH).LE.MAX) GOTO1
      MAX=A(KH)
      KP=L1(K)
    1 CONTINUE
      RETURN
      END

$IBFTC MP2
C     SUBROUTINE  MP2  DETERMINES  THE  ROW  THAT  LEAVES THE BASIS
      SUBROUTINE  MP2(L2,L20,JL2,IP,ZS,SS,KP,Q1,N,IV)
      COMMONA(3000)
      DIMENSION L2(JL2)
      INTEGER ZS,SS,Z
      V=IV
      IP=0
      IF(L20.LT.1) RETURN
      DO1I=1,L20
      KH = L2(I)*ZS+1
      KH1=KH+KP*SS
    1 IF(V*A(KH1).GT.0.)GOTO2
      RETURN
    2  Q1=V*A(KH)/A(KH1)
      IP=L2(I)
      Z=I+1
      IF(Z.GT.L20) RETURN
      DO3I=Z,L20
      KH=L2(I)*ZS+1
      KH1=KH+KP*SS
      IF(V*A(KH1).LE.0.) GOTO3
      Q=V*A(KH)/A(KH1)
      IF(Q.GE.Q1) GOTO4
      IP=L2(I)
      Q1 = Q
      GOTO3
    4 IF(Q.NE.Q1) GOTO3
      I0=L2(I)
      DO5K=1,N
      KH0=IP*ZS+K*SS+1
      KH2=IP*ZS+KP*SS+1
      KH=I0*ZS+K*SS+1
      QP=V*A(KH0)/A(KH2)
      Q0=V*A(KH)/A(KH1)
      IF(QP.LT.Q0) GOTO3
```

```
    5    IF(Q0.LT.QP)GOTO6
    6    IP=I0
    3    CONTINUE
         RETURN
         END

$IBFTC MP3
C      SUBROUTINE  MP3  TRANSFORMS  THE  SIMPLEX  TABLEAU
         SUBROUTINE  MP3(I0,I1,K0,K1,IP,KP,ZS,SS,P1,P2)
         COMMONA(3000)
         INTEGER ZS,SS,P1,P2
         KH=IP*ZS+KP*SS+1
         PIV=1./A(KH)
         II0=I0+1
         II1=I1+1
         KK0=K0+1
         KK1=K1+1
         DO1II=II0,II1
         I=II-1
         IF(I.EQ.IP) GOTO1
         KH0=I*ZS+KP*SS+1
         IF(P2.EQ.1) A(KH0) =A(KH0)*PIV
         DO2KK=KK0,KK1
         K=KK-1
         IF(K.EQ.KP) GOTO2
         KH1=I*ZS+K*SS+1
         KH2=IP*ZS+K*SS+1
         A(KH1)=A(KH1) - A(KH2)*A(KH0)
    2    CONTINUE
    1    CONTINUE
         IF(P1.NE.1) GOTO4
         DO5 KK=KK0,KK1
         K=KK-1
         KH2=IP*ZS+K*SS+1
    5    IF(K.NE.KP) A(KH2) = -A(KH2)*PIV
    4    IF(P2.EQ.1) A(KH)=PIV
         RETURN
         END
$ENTRY
```

COMPUTER OUTPUT FOR THE RESULTS REPORTED IN SECTION 5.2

TOTAL BENIFIT IS IN RUPEES

VARIABLES 1 TO 6 REFER TO IRRIGATED AREAS UNDER WHEAT, RICE, MAIZE, COTTON, SUGAR CANE, AND OTHER CROPS IN ACRES.

VARIABLES 7 TO 18 REFER TO CANAL RELEASES IN THE 12 SEASONS OF A ONE YEAR PERIOD OF OPERATION IN ACRE-FEET.

VARIABLES 19 TO 30 REFER TO TUBE-WELL RELEASES IN THE 12 SEASONS OF A ONE YEAR PERIOD OF OPERATION IN ACRE- FEET TO MEET THE WATER REQUIREMENTS OF THE CROPS.

VARIABLES 31 TO 42 REFER TO TUBE-WELL RELEASES IN THE 12 SEASONS OF A ONE YEAR PERIOD OF OPERATION IN ACRE-FEET TO DRAINAGE.

TOTAL BENEFIT= 0.98180988E 09

43	0.62980466E 07
44	0.67980466E 07
45	0.57980466E 07
46	0.37980466E 07
47	0.27980466E 07
48	0.57980466E 07
49	0.25000000E 08
50	0.30000000E 08
51	0.15000000E 06
52	0.27980465E 07
53	0.12980465E 07
54	0.47980466E 07
7	0.20195342E 06
8	0.20195342E 06
9	0.20195342E 06
10	0.20195342E 06
11	0.20195342E 06
12	0.20195342E 06
61	0.70000000E 04
62	0.70000000E 04
63	0.70000000E 04
17	0.20195342E 06
77	0.25595230E 04
18	0.20195342E 06
67	0.68233269E 04
68	0.50561937E 04
69	0.66577829E 04
70	0.95050810E 04
71	0.62305279E 04

72	0.59745728E	04
73	0.13999998E	05
74	0.13999998E	05
75	0.14000000E	05
99	0.31068062E	06
16	0.20195341E	06
78	0.83903556E	04
79	0.49977074E	04
80	0.53478480E	04
81	0.53901580E	04
82	0.61116222E	04
83	0.58188283E	04
84	0.53079726E	04
85	0.23085886E	04
86	0.34801460E	04
87	0.41525779E	04
88	0.43916298E	04
89	0.55071864E	04
90	0.59238945E	04
91	0.12659008E	06
92	0.53919512E	07
100	0.19942494E	06
5	0.10800000E	06
29	0.33906331E	06
26	0.40390081E	06
22	0.12968054E	06
23	0.22415302E	06
30	0.16184095E	06
3	0.17999991E	06
24	0.23153740E	06
21	0.21182653E	06
20	0.23803315E	06
1	0.71999992E	06
101	0.12896121E	06
106	0.72589973E	05
2	0.21541000E	06
105	0.54000000E	05
19	0.20705050E	06
6	0.45000000E	06

APPENDIX - C

A Discussion on the Results of the Cropping Policies

The solutions reported for the cropping policies in Section 5.2 can be explained by the considerations of the annual return from each crop for every acre-feet of water supplied. Table C-1 gives these informations.

TABLE C - 1

Crop. (1)	Annual water requirement in inches (2)	Average Annual yield is lbs/acre (3)	Value of crops in Rs./lb (4)	Annual value in Rs./acre (5)= (3)×(4)	Annual Return per acre-feet of water supplied $(6)=\frac{(5)}{(2)}\times 12.0$ in Rs./acre-feet
Wheat	21	900	0.50	450	257
Rice	40	800	1.00	800	240
Maize	24	1100	1.00	1100	550
Cotton	29	200	0.50	100	42
Sugar-cane	50	3000	0.75	2250	540
Other crops	24	600	0.50	300	150

We find from above table that 'maize' and 'sugar-cane' have the highest annual return per acre-feet of water supplied. They therefore enter the solution

at their maximum permissible level. Next in order is wheat and we find that 'wheat' also enters the solution at its maximum permissible level. The 'other crops' although it has a lower return than rice, also enters the solution at its maximum permissible level, because its seasonal water requirements are such that they can be met more or less by natural precipitation alone, which is available free. Water that is available after the requirements of the above crops are met, is made available for rice and 'rice' enters the solution at a level lower than its maximum permissible level. 'Cotton' which has a very poor return as compared to all the other crops considered does not enter the solution at all.